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THESIS

**AN ANALYSIS OF IEEE 802.16 AND WIMAX MULTICAST
DELIVERY**

by

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September, 2007

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AN ANALYSIS OF IEEE 802.16 AND WIMAX MULTICAST DELIVERY

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ABSTRACT

Broadband and wireless have enjoyed a massive mass market adoption in the past twenty years. Users want to be able to enjoy all applications, including multimedia, voice, and data, while still being able to access them in a mobile and fixed environment. Multicasting is a tool used in networking which allows for transmitting information to a select group of users and is especially useful for time-sensitive data which can be very large in terms of bandwidth. Current technologies, including WiFi, have difficulty handling such applications because they were not designed to handle multi-service flows concurrently. IEEE 802.16 and its emerging WiMAX technology will enable that sort of uncompromised data transmission in a wireless environment. WiMAX was designed primarily for that reason: to deliver different types of data simultaneously in fixed and mobile environments at broadband levels and ranges only dreamed of. The analysis described in this Thesis will focus on the design of WiMAX, specifically the MAC layer and describe how its features are better suited for multicasting than WiFi. Additional goals will be to look at potential applications and services of WiMAX in the telecommunications industry.

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I. INTRODUCTION

It appears as if the telecommunications industry is constantly redefining itself in an effort to satisfy its customers' needs. Lately, those needs always seem to demand higher data rates as well as a wireless feature. Broadband wireless is one of the solutions designed to meet those needs. Broadband and wireless have enjoyed a massive mass market adoption in the past twenty years. The growth of wireless mobile services went from 11 million users worldwide in 1990 to over 2 billion in 2006 [1]. During that same period, the Internet has grown to over a billion users. The integration of all these mobile users with the Internet is a large part of the drive for higher data rates. Users want to be able to enjoy all of the applications, including multimedia, voice, and data, while still being able to access them in a mobile and/or fixed environment. IEEE 802.16 and its WiMAX technology are part of the solution which will enable that sort of uncompromised data transmission in a wireless environment. This technology also has huge advantages over some of its alternatives as it was designed to support Quality of Service (QoS) as one of its major features. Many other technologies, including WiFi, have difficulty handling such applications because they were not designed to handle simultaneous flows concurrently. WiMAX was designed primarily for that reason: to deliver different types of data simultaneously in fixed and mobile environments at broadband levels and ranges only dreamed of.

A. WIMAX AND MULTICASTING TIME-SENSITIVE DATA

WiMAX is a technology developed by the WiMAX forum with the intention to implement the IEEE 802.16 standard and bring it to reality. Currently, the industry is in the middle of introducing these products to commercial users. Major telecommunication industries are investing billions of dollars into this technology with the hope of integrating it into their networks. For example, Sprint Nextel has invested more than 3.5 billion dollars in WiMAX technology since 2006 and intends to launch Mobile WiMAX broadband services in initial markets by year-end 2007 with a larger roll-out encompassing at least 100 million people by year-end 2008 [2]. This is an emerging

technology and looks like it will have a tremendous impact on broadband wireless. WiBro, the WiMAX equivalent in South Korea, is already in existence and operating at a high level [2].

So what does WiMAX offer that some of the alternative network technologies like cellular and WiFi don't? Is there a demand out there in the telecommunications industry which is not being met by current technologies? Personal digital assistants (PDAs) are beginning to dominate the cellular landscape. These devices are limited by the data rates and costs to maintain them due to necessary communications infrastructure. It could be argued that users today want to be able to watch a movie, talk on the phone, check their e-mail, browse the Internet while roaming around a city or driving in their car for that matter. Cellular companies are beginning to offer some of these services but are finding it more and more difficult to satisfy their users' bandwidth desires. There is also a growing desire for laptop and desktop users to access these same services.

Multicasting is a tool used in networking which allows for transmitting the same information to a select group of users at the same time. The key is that it is a group of users who may or may not be directly connected with each other and could be spread out over the network. The goal is to transmit this data in an efficient manner with no bandwidth wasted. This is optimization at its simplest. Multicasting is especially useful for time-sensitive data that uses very large amounts of bandwidth. Buffering can be helpful for error correction and network independency but there still will be a need to transmit this data to a group of individuals at a large bandwidth. Some technologies are better suited for these types of applications than others. The analysis described in this Thesis will focus on the design of WiMAX, specifically the MAC layer and describe how its features are better suited for multicasting than WiFi. Additionally, we will describe potential applications and services of WiMAX in the telecommunications industry.

1. The Problem - Multicast Challenges in WiFi

IEEE 802.11 and its correlating WiFi technology is a ubiquitous WLAN technology prevalent on almost every telecommunications device. It is the leading wireless technology for personal computers and it is unchallenged in the local area

network [3]. There has been much research to show that there are significant limitations with this technology involving multicast delivery. Dujovne and Turletti's paper, "Multicast in 802.11 WLANs: An Experimental Study," shows how these limitations are due to its design features, especially with regards to its MAC layer. The paper also states that its original design was primarily for data transfer. It was not designed for applications such as high-data multimedia or gaming that is becoming more prevalent today. The technology has trouble coping with these types of transmissions. One way that many networks, both wired and wireless, deal with such high-end applications is by multicasting them so that the links are not overrun by redundant transmissions. Multicast delivery is useful when a group of users wish to watch a multimedia application or something similar simultaneously. Some examples of applications that can be utilized by multicast delivery are video tele-conference (VTC), video downstreaming, gaming, or even system updates.

The problem is that the current WiFi technology and its IEEE 802.11 standard do not handle multicast transmissions well. They are not scalable and tend to overwhelm the networks when other applications are running. There is also a problem of efficiency, flow control and wireless communications tend to be lossier than their wired counterparts. There has been much research in dealing with these issues and there have been successful results from these newer innovations for WiFi [3]. The problem is that they would require a completely new structural design of the WiFi technology. This may be unnecessary to pursue as there is an emerging technology, WiMAX and its IEEE 802.16 standard, which is more than capable of handling these applications without any changes to its design. Its design fits perfectly into the demands for these types of applications.

2. Scope of Thesis

In this thesis we will describe the current technologies in place with relation to broadband wireless and cellular infrastructure. We will also discuss IEEE 802.11 and its corresponding WiFi technology as well as its limitations and challenges with multicast applications. This thesis will focus on analyzing the IEEE 802.16 standard and its emerging WiMAX technology directly related to multicast and time-sensitive high-data

applications. The Physical layer and the MAC layer will be a point of emphasis when discussing the design of this technology. Security, integration, and regulatory issues are not in the scope of this thesis. Potential WiMAX services and applications will also be a point of emphasis for this thesis.

B. RESEARCH OBJECTIVES

There has been much research and emphasis on redesigning current wireless technologies in an attempt to accommodate the demands of high-end applications. The objective of this thesis is to show that WiMAX and the IEEE 802.16 standard are already designed for this and further research into legacy technologies is unnecessary. WiMAX is designed for multicast services and high-data applications due to its design and QoS standards. The objective of this thesis is to show that IEEE 802.16 and WiMAX were designed for such applications whereas other technologies, such as WiFi, would need to be redesigned to adequately fulfill these requirements.

C. RESEARCH QUESTIONS

1. What are the prevalent characteristics of wireless technology?
2. What are the differences/similarities between 802.11 and 802.16?
3. Describe in detail the technical aspects behind 802.11 and 802.16.
4. What are the WiMAX and WiFi relationships to cellular technology? Do they relate?
5. What is Multicast? Is there a growing need for multicast in wireless technology?
6. How does multicast in 802.11 work? What are the challenges associated with it? What are some solutions?
7. Are these solutions proven to work or are there simulations that show they should work?
8. How does multicast in 802.16 function? What are the parameters of the Physical Layer and MAC Layer of WiMAX?
9. Is 802.16 a better venue for multicast services than 802.11? Why?
10. What are some other potential applications for WiMAX? Are there Military, Civil, and Business applications?

D. ORGANIZATION

The remainder of this thesis follows the structure described below:

Chapter II focuses on the background of current wireless communications. This is to include cellular, IEEE 802.11 and its WiFi technology, and IEEE 802.16 and its emerging WiMAX technology.

Chapter III describes delivery services over a network. It will also describe challenges WiFi technology faces with regards to multicast delivery of high-data time-sensitive applications. There are solutions that are being researched and these solutions will be discussed as well.

Chapter IV will analyze the IEEE 802.16 standard and in particular the physical and MAC layers and show that it is already designed for such applications. This chapter will also describe potential applications and services of WiMAX.

Chapter V will discuss future works as a result of this thesis and conclusions.

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II. WIRELESS COMMUNICATIONS

This chapter consists of two main parts. The first section summarizes the principles of cellular technology and its evolution. The second section describes wireless basics, the IEEE 802.11 standard and its corresponding WiFi technology as well as the emerging IEEE 802.16 standard and its corresponding WiMAX technology. The actual standards themselves, in addition to other resources noted, were used extensively when describing these wireless standards.

A. CELLULAR TECHNOLOGY

A cellular network is a radio network made up of a number of radio cells (or just cells) each served by a (geographically) fixed transmitter, known as a cell site or base station. These cells are used to cover different areas in order to provide radio coverage over a wider area than the area of one cell. Cellular networks are inherently asymmetric with a set of fixed main transceivers each serving a cell and a set of distributed (generally, but not always, mobile) transceivers which provide services to the network's users. This section will focus on cellular fundamentals, air interface techniques, and the evolution of cellular technology. Much of this information on cellular technology was derived from Thomas Rappaport's, Wireless Communications: Principles and Practices [4] and Ionnis Chatziioannidis' thesis, "High speed Internet access using cellular infrastructure [7]."

1. Principles of Cellular Networks

Modern cellular systems share common features when describing the makeup of their systems. These features are broken down into two sets – hardware and functionality. Some of these common features are:

Hardware:

- **Mobile Station (MS)** – simply known as the mobile phone, this is the phone the subscriber uses for access to the network.

- **Base Transceiver Station (BTS)** – also known as the base station, the antenna which provides the interface for every MS. It is allocated only a fraction of the total number of channels or frequencies available to the entire system.
- **Base Station Controller (BSC)** – Just like its name suggests, A BSC controls a number of BS's as well as its mobile management.
- **Mobile Switching Center (MSC)** – This is the switch to which base stations connect and it is responsible for call routing and interconnection with the Public Switched Telephone Network (PSTN). A general description of a cellular network is visible in Figure 1.

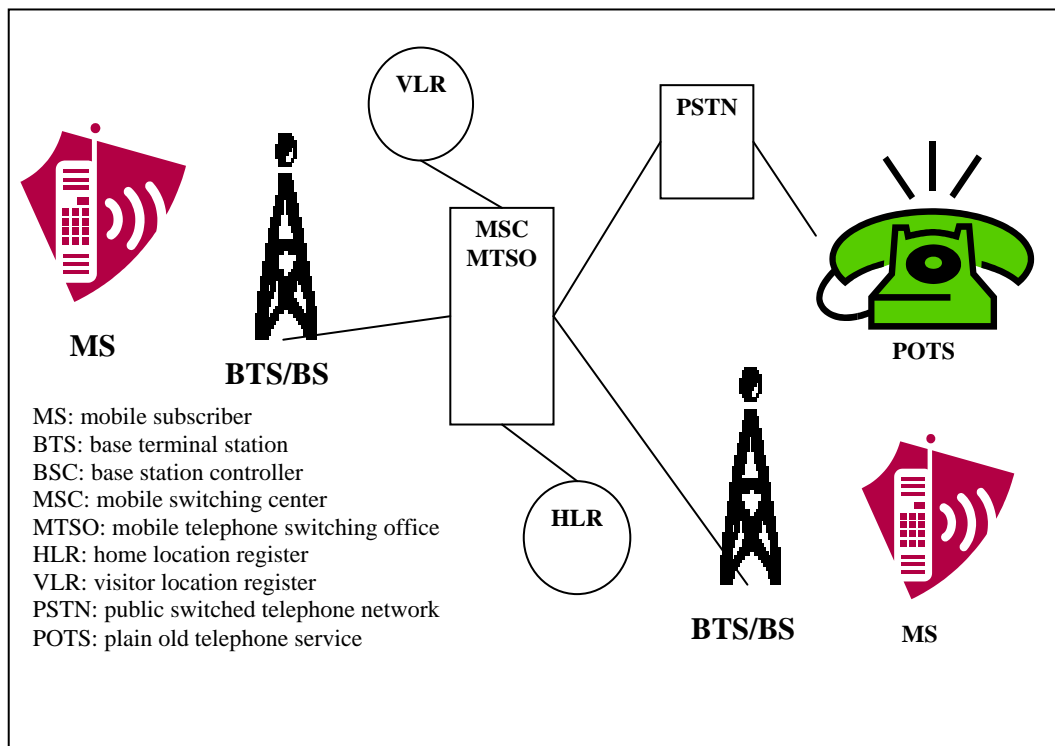


Figure 1. A Common Cellular Network (After: [4]).

Functionality:

- **Cell** – This is the effective coverage of the base station. The radius depends on a multitude of environment parameters, power level, and population density.
- **Frequency Reuse** – This is a technique that maximizes the number of mobile phones in a given area by assigning a part of the total available frequency spectrum in different base stations. The goal is to maximize the number of potential users with a limited frequency spectrum while limiting interference between the base stations. Figure 2 shows how one approach to frequency reuse can be carried out by a cellular network.

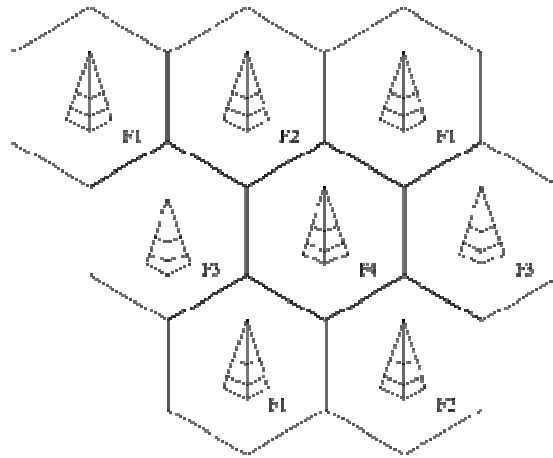


Figure 2. A visual description of frequency reuse (From: [4]).

- **Handoff** – This is the transition a call will go through when made by an MS, when it transitions from one radio channel to another. It can occur under one of the following conditions:
 - Call is passed from one base station to another when the range from the first is insufficient.
 - Call is passed within the same base station on different frequencies due to traffic density.

- Call is passed when MS is changing BSC.
- Call is passed when MS is changing MSC.
- A hard handoff is when an MS is assigned a different radio channel.
- A soft handoff is when an MS is able to communicate with two distinct BTS simultaneously.
- **Roaming** – the situation when an MS is visiting another service provider and is being serviced by one of their BTS. Many countries and regions define this differently according to their market trends, policies, or laws. Recently, many cellular companies have gone global and they will have plans defined that allow for this type of feature nationally and even internationally.

2. Air Interface Techniques

Cellular providers differ in network implementations, but some of the techniques used in the air interface are standard. These techniques are: duplex, multiple access, multiplexing, and modulation techniques.

a. Duplex Techniques

Frequency Division Duplex (FDD) and Time Division Duplex (TDD) are two techniques used to ensure duplex (two-way) communications between users. In FDD, two distinct bands of frequencies are used for each user, as shown in Figure 3. The first band is called the forward channel and is used for communication from the network to the mobile user. The second channel is called the reverse channel and is used for the mobile user to the network. There is a channel separation which is actually a separation frequency that prevents interference. FDD is most useful in systems expecting symmetric traffic, because the two channels assigned are equal bandwidth. The second duplex technique is TDD, as shown in Figure 4, and in this technique, each user shares a single radio frequency with the base station. This is accomplished by timeslicing the channel

fast enough so the transmitters and receivers see a continuous flow of information. The difference is that the mobile users are allocated time slots to exchange their data. TDD is useful in systems that have asymmetric traffic patterns, because the time slots can be allocated asymmetrically, something FDD has difficulty doing dynamically. Regardless of the duplex method utilized, both the base station and the remote user need to have both transmission and reception capability, usually in the form of a transceiver.

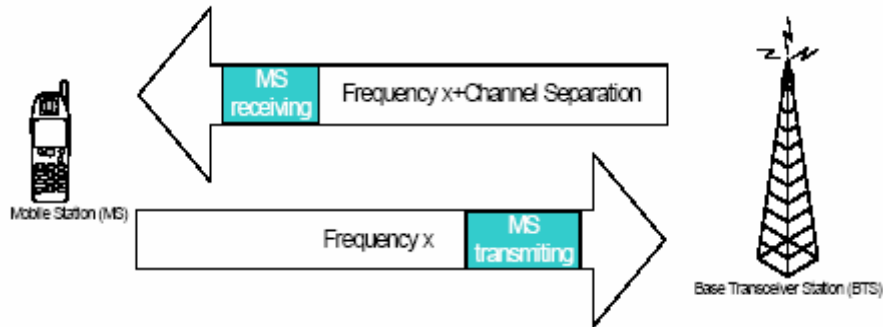


Figure 3. FDD Forward and Reverse Channels.

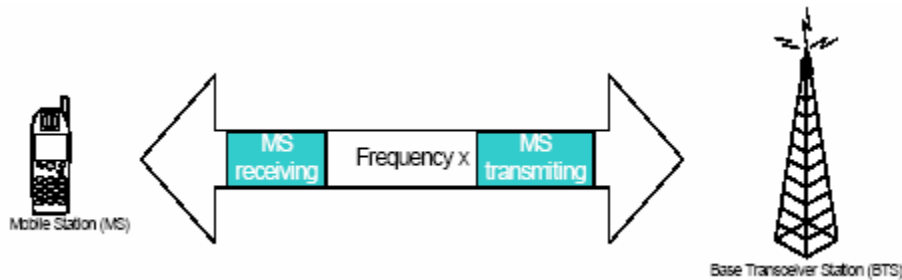


Figure 4. A TDD Channel.

b. Multiple Access

Multiple Access techniques allow for a large number of users within the same bandwidth. Their primary purpose is to separate the bandwidth in a manner which efficiently establishes access to the maximum number of users at any given time. Some of the more common techniques are Frequency Division Multiple Access (FDMA), Time Division Multiple Access (TDMA), and Code Division Multiple Access (CDMA).

- FDMA, as shown in Figure 5, gives every user a specific frequency. It breaks the bandwidth into user slots. FDMA can be used with either FDD or TDD.

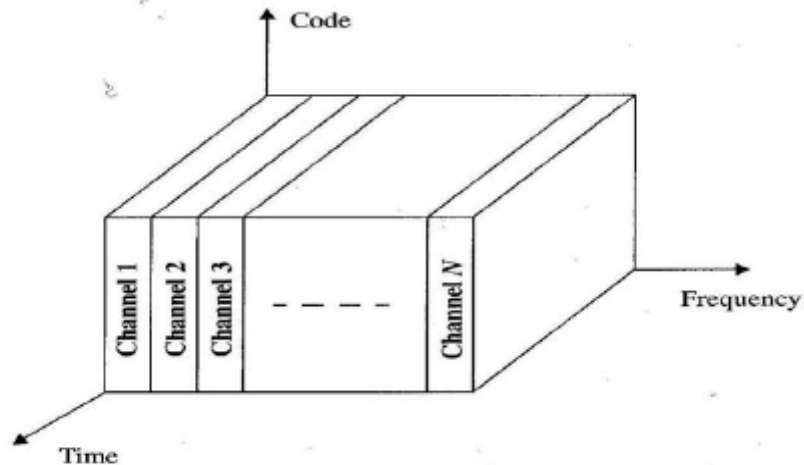


Figure 5. FDMA slicing (From: [3]).

- TDMA, as shown in Figure 6, breaks the bandwidth into time slots where every user is given the whole bandwidth for a limited time. It also can be used with TDD or FDD.

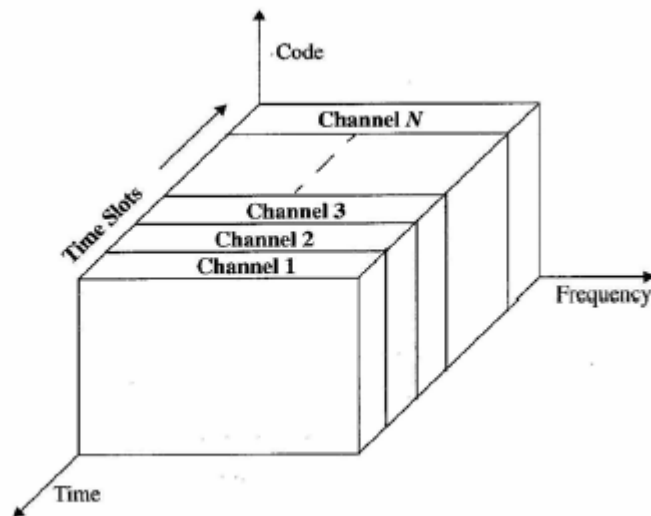


Figure 6. TDMA slicing (From: [3]).

- Lastly, CDMA utilizes the Direct Sequence Spread Spectrum technique (DSSS) in which a user's data stream is spread over a larger wideband spectrum. As shown in the Figure 7, a user's data is spread into a wider spectrum by being multiplied with a higher data rate spreading code. The resulting spread signal is then modulated and transmitted. The receiving end recovers the original data by multiplying the same spreading code with the received signal. The CDMA technique allows multiple users to communicate with the network simultaneously by being multiplexed with DSSS into a single radio channel. The key is that each user is differentiated from each other by a unique spreading code which enables the receiver to differentiate the signal. Since the capacity does not rely on frequency range, it is theoretically possible for there to be an unlimited number of users on the channel. However, tests have shown that roughly 64 users on the channel at once allows for good hearability and tolerable interference [7]. CDMA can also be used with either TDD or FDD.

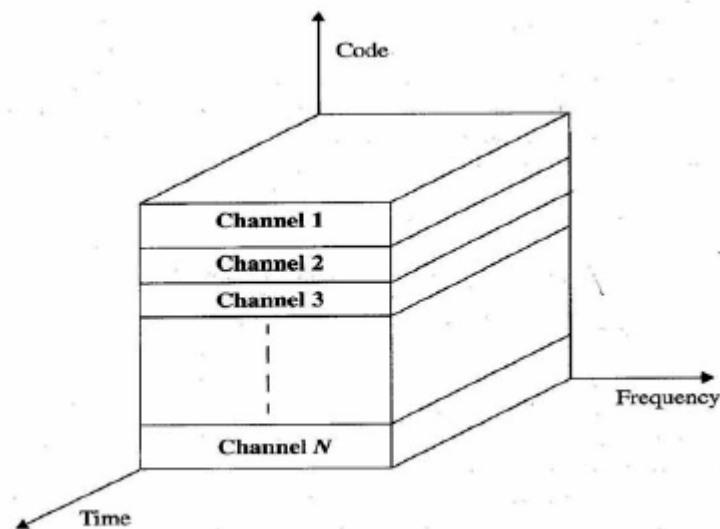


Figure 7. CDMA slicing (From: [3]).

c. Techniques in Modulation

Modulation in telecommunications refers to the process of varying a periodic waveform, or tone, in order to use that signal to convey a piece of information [4]. In other words, varying the frequency or increasing and decreasing the power of the signal could be ways to convey a message so long as both the receiver and transmitter know the protocol and codes ahead of time. Normally, a high-frequency sinusoid waveform is used as a carrier signal. The three key parameters of a sine wave are its amplitude, phase, with respect to a clock or other signals, and its frequency. All three of these parameters can be modified in such a way to obtain a unique sine wave, or piece of information. There are two basic types of modulation: analog and digital. Analog modulation transfers an analog lowpass signal over an analog bandpass channel. Interestingly enough, First Generation cellular technology actually used analog modulation due to their analog signals. Digital modulation transfers a digital bit stream over an analog bandpass channel. Generally, digital modulation is described as linear when the amplitude of the transmitted signal is a linear proportion of the modulated digital signal or non-linear when the amplitude is constant. There are many different types of linear modulation but some of the more widely used are:

- Binary Phase Shift Keying (BPSK)
- Differential Phase Shift Keying (DPSK)
- Quadrature Phase Shift Keying (QPSK)

Another type of modulation which will be discussed in greater detail later in this chapter is Orthogonal Frequency Division Multiplexing (OFDM). It is used extensively in both the 802.11 and the 802.16 standards.

3. Cellular Technology Evolution

Cellular technology was developed by Bell Labs in 1978. The first experimentation of this technology was in Chicago and was known as the Advanced Mobile Phone Service. It was rolled out to the public in 1983 but was too costly and

cumbersome for most users. This is a normal adjustment for most newer technologies until their evolution allows for widespread use. From 1978 – 1990, most cellular network technology was of the First Generation (1G) variety [7]. Many 1G cellular networks surfaced on almost every continent in the Western World. All of these networks used frequency modulation (FM), FDMA, and FDD schema.

The rise of Second Generation Networks (2G) in 1990 was the solution to the problem of limited user capacity per cell. It uses digital modulation formats and TDMA/FDD and CDMA/FDD techniques [7]. All 2G networks offer triple spectrum efficiency. The most well-known technologies are Global Systems Mobile (GSM), Interim Standard 54 (IS-54), Pacific Digital Cellular (PDC), and Interim Standard 95 (IS-95). GSM is still the largest and most widely worldwide spread system used in Asia, Europe, Australia, South America, and the United States in a smaller degree. It still boasts almost 90% of the cellular market worldwide. 2G technologies send the data over circuit-switched modems in a single circuit-switched voice channel. The data rate for 2G technology hovers around 10Kbps. The need for increased throughput data rates in data transfer led to the evolution of two and a half generation networks (2.5). 2.5G networks are designed to support web browsing and its Hyper Text Transfer Protocol (HTTP) as well as Wireless Access Protocol (WAP) which allows web viewing on smaller handheld devices [7].

Third Generation Cellular Networks (3G) spawned off additional needs of Internet access. Since the Internet had become such a common and powerful media, it was only a matter of time until the demand for such access was desirable for cellular networks. 3G Cellular Networks provide high speed Internet access, live video communications, as well as the simultaneous data and voice transmit. Some of the more popular 3G technologies are Wideband CDMA, Code Division Multiple Access 2000, Time Division Synchronous CDMA, and Digital Enhanced Cordless Telephone [7]. Fourth Generation Cellular Networks (4G) is where much of the research and development is focused right now. Its goal is even larger bandwidth for the cellular network.

B. IEEE 802 – LAN/MAN

The IEEE forum is formally known as the Institute of Electrical and Electronics Engineers and it is an international non-profit organization for the advancement of technology related to electricity. It boasts over 360,000 members in 175 countries and it is solely responsible for creating standards in electronics [4]. The IEEE 802 LAN/MAN standard focuses on developing Local Area Network standards and Metropolitan Area Network Standards. Table 1 shows a list of the standards in the IEEE 802 family. One in particular is 802.3 which is Ethernet technology and is ubiquitous in most wired networking.

802	Overview	Basics of physical and logical networking concepts.
802.1	Bridging	LAN/MAN bridging and management. Covers management and the lower sub-layers of OSI Layer 2, including MAC-based bridging (Media Access Control), virtual LANs and port-based access control.
802.2	Logical Link	Commonly referred to as the LLC or Logical Link Control specification. The LLC is the top sub-layer in the data-link layer, OSI Layer 2. Interfaces with the network Layer 3.
802.3	Ethernet	"Granddaddy" of the 802 specifications. Provides asynchronous networking using "carrier sense, multiple access with collision detect" (CSMA/CD) over coax, twisted-pair copper, and fiber media. Current speeds range from 10 Mbps to 10 Gbps.
802.4	Token Bus	Disbanded
802.5	Token Ring	The original token-passing standard for twisted-pair, shielded copper cables. Supports copper and fiber cabling from 4 Mbps to 100 Mbps. Often called "IBM Token-Ring."
802.6	Distributed queue dual bus (DQDB)	"Superseded Revision of 802.1D-1990 edition (ISO/IEC 10038). 802.1D incorporates P802.1p and P802.12e. It also incorporates and supersedes published standards 802.1j and 802.6k. Superseded by 802.1D-2004."
802.7	Broadband LAN Practices	Withdrawn Standard. Withdrawn Date: Feb 07, 2003. No longer endorsed by the IEEE.
802.8	Fiber Optic Practices	Withdrawn. Standards project no longer endorsed by the IEEE.

802.9	Integrated Services LAN	Withdrawn. Standards project no longer endorsed by the IEEE.
802.10	Interoperable LAN security	Superseded **Contains: IEEE Std 802.10b-1992.
802.11	Wi-Fi	Wireless LAN Media Access Control and Physical Layer specification. 802.11a,b,g,etc. are amendments to the original 802.11 standard. Products that implement 802.11 standards must pass tests and are referred to as "Wi-Fi certified."
802.12	Demand Priority	Increases Ethernet data rate to 100 Mbps by controlling media utilization.
802.13	Not used	Not used
802.14	Cable modems	Withdrawn. Standards project no longer endorsed by the IEEE.
802.15	Wireless Personal Area Networks	Communications specification that was approved in early 2002 by the IEEE for wireless personal area networks (WPANs).
802.15.1	Bluetooth	Short range (10m) wireless technology for cordless mouse, keyboard, and hands-free headset at 2.4 GHz.
802.15.3a	UWB	Short range, high-bandwidth "ultra wideband" link
802.15.4	ZigBee	Short range wireless sensor networks
802.15.5	mesh network	<ul style="list-style-type: none"> • Extension of network coverage without increasing the transmit power or the receiver sensitivity • Enhanced reliability via route redundancy • Easier network configuration - Better device battery life
802.16	Wireless Metropolitan Area Networks	This family of standards covers Fixed and Mobile Broadband Wireless Access methods used to create Wireless Metropolitan Area Networks (WMANs.) Connects Base Stations to the Internet using OFDM in unlicensed (900 MHz, 2.4, 5.8 GHz) or licensed (700 MHz, 2.5 – 3.6 GHz) frequency bands. Products that implement 802.16 standards can undergo WiMAX certification testing.

Table 1. 802 LAN/MAN Standards (From: [1], [4], [5], [8]).

1. Wireless Computing Basics

Wired networking is reliable, fast but can be expensive due to the need for wired infrastructure [1]. This expense led to researchers looking for wireless solutions. The IEEE 802.11 standard was completed in 1997 and many revisions and improvements have been produced since then [8]. WiFi is an application of the IEEE 802.11 standard. It follows the standard but does not necessarily include everything in the standard. Generally, wireless technology offers network connectivity without being tethered off of a wired network. This technology was designed to combat the high installation and maintenance costs incurred by traditional additions, deletions and changes experienced in wired LAN infrastructure. Ideally, users of wireless networks want the same services and capabilities that they have come to expect with wired networks. With the growth of the Internet and its demand on large bandwidth as well as high-data rate for such applications as video streaming and gaming, this has posed quite a challenge for wireless networks. Many of the standard improvements are addressing this problem in almost all wireless technologies, including cellular, WiFi, and even WiMAX.

In the early days of computer networking, different vendors used systems with incompatible architectures. This required customers to stay with a single vendor. To remedy this situation, The International Standardization Organization (ISO) developed a seven-layer model for communications systems.

- Physical Layer – deals with the transfer of bits over an actual communication channel.
- Data Link Layer - deals with the transfer of frames. It includes framing and address information, as well as flow information.
- Network Layer – provides for the transfer of packets across a communication network. It also deals with finding a path in the network (routing) and handles congestion from temporary increases in traffic.
- Transport Layer – deals with the transfer of complete messages.

- Session Layer – controls data exchange.
- Application Layer – provides services to the various applications.

The IEEE 802 standards deal with the lowest two layers in the ISO open systems interconnection (OSI) reference model: the physical and the data link layer. Furthermore, IEEE 802 specifies the data link layer in two sublayers, logical link control (LLC) and medium access control (MAC). The LLC is situated above the MAC layer. It is common to all IEEE 802 standards. Figure 8 gives a clear representation of the OSI model.

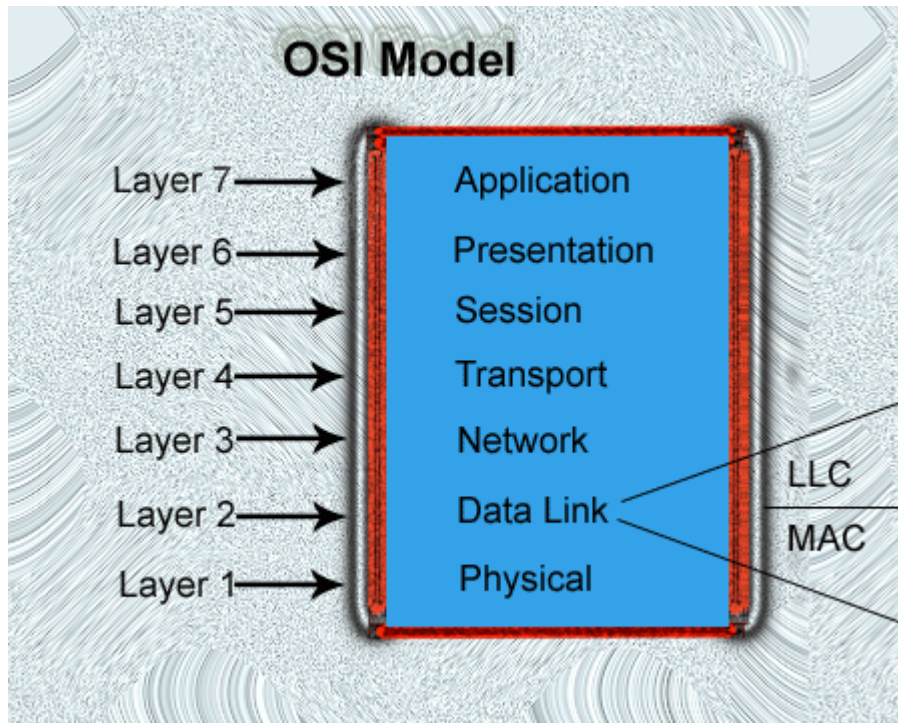


Figure 8. Seven-Layered OSI Model (From: [3]).

a. MAC Requirements

The MAC protocol defines the way the medium is shared among multiple users. The medium in which wireless devices operate is a good example of a shared medium; here the medium is the space through which the radio waves propagate. The ultimate goal of the MAC for wireless communication is to allow a large group of otherwise uncoordinated users to efficiently use this shared medium. Therefore the choice

of a MAC protocol depends on the nature of the traffic and the performance demands of the users as well as the signaling infrastructure.

There are primarily two general types of traffic: periodic and bursty. When the interarrival variance between messages is very small, traffic is said to be periodic. Signals such as video generate periodic traffic. Periodic traffic requires a limit on the maximum end-to-end delay and the delay variation (jitter). Since the delay depends on the time to assign channel access, the MAC design has a big influence on the channel setup signal delay. The data rate of a periodic traffic source is approximately constant. Therefore, the use of a dedicated, circuit-switched connection for periodic traffic is justified. Bursty traffic is characterized by messages of arbitrary length separated by intervals of random duration. Data communication (Internet, e-mail, file sharing, voice) is an example of bursty traffic. The delay and jitter are not important for bursty traffic. A bursty traffic source leads to a data rate that varies considerably. The peak data rate is much higher than the average data rate. Packet-switched connections perform much better for bursty traffic. Because communication systems must not only support Internet access but also voice and video, both traffic types must be handled. This requirement makes the design of a MAC layer protocol a difficult task. In addition, in wireless networks, the wireless channel is also the only means to coordinate the stations in the network.

Another challenge the MAC must deal with has to do with access contentions. In general, access methods fall into three general categories: contention methods, polling methods, and TDMA methods. Contention protocols are also called CSMA or listen-before-talk. If a station has data to transmit, it senses the channel for a certain period of time before transmitting. For each station, the length of this time period is random within a predefined interval. Ethernet is a good example of this type of protocol. These protocols are well suited for bursty traffic. But they have one fundamental disadvantage, there are no delay guarantees. As a result, purely contention systems are not as efficient for periodic traffic as some other systems, such as time-slotted systems[1].

In slotted systems, such as TDMA, all users are effectively synchronized and have different time slots of certain duration assigned to them in different fashion.

This is very well suited for periodic traffic. Not so for bursty traffic because a station will have a time slot assigned to it even if it does not have data to transmit. A significant problem for TDMA protocols is selecting time slot duration or packet size. If the time slot durations are chosen to match the largest message lengths, shorter messages will not use the channel effectively. On the other hand, if shorter slot sizes are used, the delivery of longer messages will require several time slots. Unfortunately, the message size cannot be known in advance and is likely to change dynamically.

The polling access method requires a central station. This station controls the network by effectively polling the other individual stations. When a station has data to send, it will send it in response to a poll. Stations that have periodic data to transmit usually can request to be polled on a periodic basis.

Polling is efficient in the sense that it achieves dynamic resource allocation. However, there are two main disadvantages to this method. First, the overhead for maintaining the global queue can be high due to the number of users. Second, all data must pass through a central station, even if it is not destined for the central station. A central station in a sense, manages the network by this polling method [8].

Another distinction between access protocols deals with the user's share of the network. There are two main distinctions: static and dynamic. Static allocation MACs allow for a guarantee of a share of the network. The disadvantage is that it can be inefficient because the resources cannot be transferred among users as user requirements change over time. MACs with dynamic allocation try to provide network resources only to users that have data to transmit. Compared with other dynamic-allocation protocols, contention-based MACs are easier to implement. This ease comes from the fact that users can join or leave the network at any time. This is why Ethernet is far more popular than the contention-free token ring network [1]. This feature is vital to wireless networks because users may roam about freely.

The basic requirements of the MAC are:

- The MAC protocol must be independent of the physical layer.

- The access mechanism must be efficient for both bursty and periodic traffic.
- The MAC must be able to handle mobile users [5].

b. PHY Requirements

The physical layer or PHY is the first layer of the seven layer OSI model and is responsible for transporting bits between adjacent systems over the medium. The PHY performs two main functions, depending on whether the device is in transmit or receive mode. In transmit mode, the PHY receives a bit stream from the MAC layer and performs signal processing operations such as error-correcting coding and modulation to convert the bit stream into an electric signal that is then supplied to the antenna. In receive mode, the antenna receives the electric signal from the antenna and reverses the identical process from transmission. Besides these two functions, IEEE 802 standards also require the physical layer to provide carrier-sense indication back to the MAC [8]. Carrier-sense is an important feature because it ensures that the sender senses its environment prior to transmitting. This helps avoid collision.

Due to the nature of the medium (interference, static noise), wireless channels lead to bit error rates higher than wired channels. So error-control schemes are important. There are three general types of error control coding schemes used:

- Block codes
- Convolution codes
- Automatic repeat request (ARQ) schemes

These error-correcting codes are designed to prevent against random errors not burst errors. However, in wireless communications, most errors are burst errors due to a result in a change to the medium like a power jolt, or just basically interference. There exists a technique which reduces these types of bursty errors known as interleaving. With interleaving, the symbols contained in one code block are not transmitted in consecutive order, but instead are dispersed among other transmitted symbols so that a signal fade is

less likely to impose a dense burst of errors on individual code block. If interleaving is done over a long period of time, then the error can be made more secluded. The general requirements of the PHY are bandwidth efficiency and power efficiency. Due to the ever-growing demand for increased data rates, bandwidth efficiency is becoming more important.

Both the PHY and the MAC layers can be composed of sublayers. The interface between the MAC and the PHY, like the interface between any two protocol layers, is called the service access point (SAP). The MAC provides services to the layer above it, normally IP, while the PHY provides service to the MAC, as shown in Figure 8.

2. IEEE 802.11 and Its Corresponding WiFi Technology

The IEEE 802.11 working group began in 1990 and its motivation was to create a “wireless Ethernet” [5]. It was intended to provide connectivity where wiring was inadequate to support wired LANs. Ethernet needs CAT5 cabling which is not available in older homes and buildings. Another motivation for IEEE 802.11 was the allocation of the 2.4 GHz band in the United States for unlicensed devices by the FCC in 1986. Figure 9 summarizes the architectural view. There are four major parts to 802.11: The MAC of the data link layer, the PHY, the IEEE 802.1x layer, and upper-layer authentication protocols. The data link layer consists of an IEEE 802.1X layer and a MAC sublayer. The physical layer consists of two sublayers: a physical layer convergence protocol (PLCP) sublayer and a physical medium-dependent (PMD) sublayer. The PHY and the MAC have management sub entities, which communicate with the station management entity.

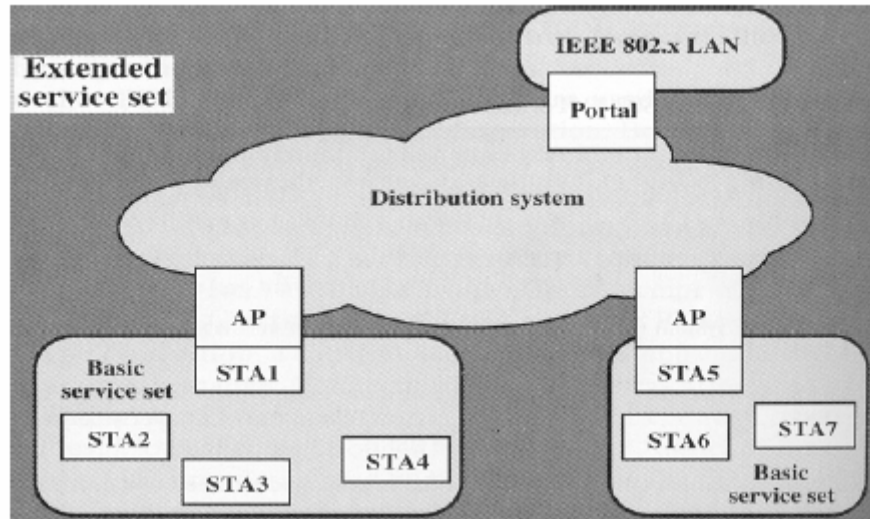


Figure 9. Basic Architecture View of 802.11 (From: [3]).

There was much research on the medium-access protocol of IEEE 802.11 before deciding on carrier-sense multiple access with collision avoidance (CSMA/CA)[9]. This is quite similar to IEEE 802.3 version of CSMA with collision detection (CD). The difference between the two is that in wireless communications, detection is not possible. A transmitting station cannot reliably detect collisions because the transmitted signal will be stronger than the received signal. The MAC sublayer's main purpose then is to ensure that the upper layers of the OSI model are not aware of the unreliability of the wireless channel [5]. This also allows for the concept of mobility. The standard allows a mobile station to roam freely throughout a WLAN while appearing to remain stationary to the protocols above the MAC.

This section will focus on the 802.11 architecture, the 802.11 MAC and PHY layers, and the evolution of the IEEE 802.11 standard. Security and all related issues in the IEEE 802.11 standard are out of the scope of this thesis.

a. IEEE 802.11 Architecture

The IEEE 802.11 logical architecture contains several main components: station (STA), wireless access point (AP), independent basic service set (IBSS), basic

service set (BSS), distribution system (DS), and extended service set (ESS). Some of the components of the 802.11 logical architecture map directly to hardware devices, such as STAs and wireless APs. The wireless STA contains an adapter card or a NIC card which many PCs and laptops have which are either embedded or slotted. The wireless AP functions as a bridge between the wireless STAs and an existing network backbone for network access. An IBSS is a wireless network, consisting of at least two STAs, used where no access to a DS is available. An IBSS is also sometimes referred to as an ad hoc wireless network. A BSS is a wireless network, consisting of a single wireless AP supporting one or more wireless clients. A BSS is also sometimes referred to as an infrastructure wireless network. All STAs in a BSS communicate through the AP. The AP provides connectivity to the wired LAN and provides bridging functionality when one STA initiates communication to another STA or a node on the DS. An ESS is a set of two or more wireless APs connected to the same wired network that defines a single logical network segment bounded by a router (also referred to as a subnet). The APs of multiple BSSs are interconnected by the DS, as shown in Figure 10. This allows for mobility, because STAs can move from one BSS to another BSS. APs can be interconnected with or without wires: however, most of the time they are connected with wires. The DS is the logical component used to interconnect BSSs. The DS provides distribution services to allow for the roaming of STAs between BSSs.

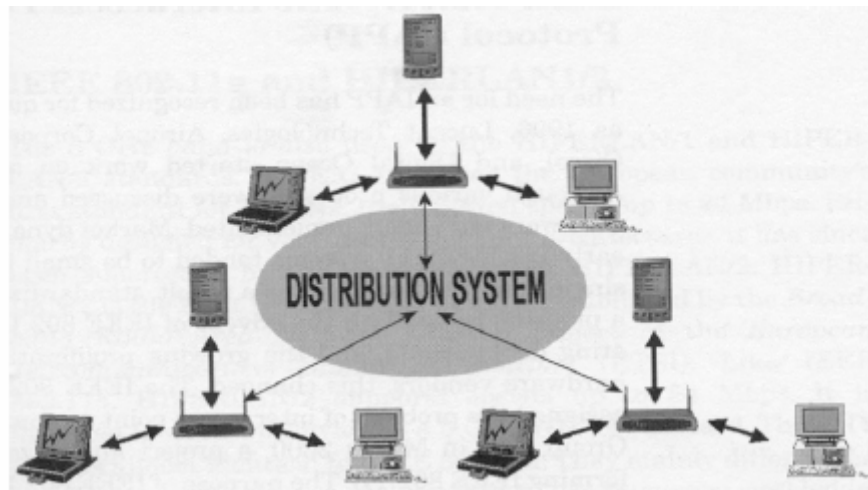


Figure 10. An Extended Service Set (From: [6]).

IEEE 802.11 defines two operating modes: Infrastructure mode and Ad hoc mode. In both modes, a Service Set Identifier (SSID), also known as the wireless network name, identifies the wireless network. The SSID is a name configured on the wireless AP (for infrastructure mode) or an initial wireless client (for ad hoc mode) that identifies the wireless network. The SSID may be periodically advertised by the wireless AP or the initial wireless client using a special 802.11 MAC management frame known as a beacon frame. In infrastructure mode, there is at least one wireless AP and one wireless client. The wireless client uses the wireless AP to access the resources of a traditional wired network. The wired network can be an organization intranet or the Internet, depending on the placement of the wireless AP. A typical 802.11 WLAN is shown in Figure 11.

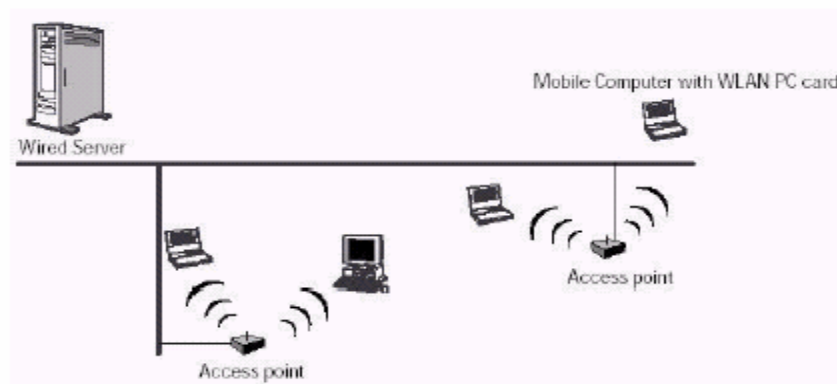


Figure 11. Typical WLAN configuration (From: [7]).

In ad hoc mode, wireless clients communicate directly with each other without the use of a wireless AP. Ad hoc mode is also called peer-to-peer mode. Wireless clients in ad hoc mode form an independent basic service set (IBSS). One of the wireless clients, the first wireless clients in the IBSS, takes over some of the responsibilities of the wireless AP. These responsibilities include the periodic beaconing process and the authentication of new members. This wireless client does not act as a bridge to relay

information between wireless clients. Ad hoc mode is used to connect wireless clients together when there is no wireless AP present. The wireless clients must be explicitly configured to use ad hoc mode.

b. Data Link Layer: Medium-Access (MAC) and Real-Time Traffic

When the IEEE 802.11 working group started its research on the MAC, it was assumed that the data sent across the medium would be primarily computer data communications. It did not envision that there would be a need for real-time data like voice or downstream video. Since the MAC is of the CSMA nature, it is optimal for computer data communications, but not real-time data. One can use this type of data communication to transport real-time data but it is not what it was designed for so there have been many amendments and changes to fit this into its specifications as we shall discuss in Chapter 3.

Providing different levels of quality of service (QoS) is widely recognized as one of the most important ways to achieve this. The nature of real-time traffic is different from data applications. The main QoS factors are:

- Bandwidth
- End-to-end delay or latency
- Latency jitter
- Signal quality and packet loss

There are two sublayers within 802.11's data link layer. They are the Logical Link Control (LLC) and the Media Access Control (MAC). 802.11 uses the same 802.2 LLC and 48-bit addressing as other 802 LANs, allowing for very simple bridging from wireless to IEEE wired networks, but the MAC is unique to WLANs. The 802.11 MAC is very similar in concept to 802.3, in that it is designed to support multiple users on a shared medium by having the sender sense the medium before accessing it. However, in an 802.11 WLAN, collision detection is not possible unlike Ethernet due to the "near/far" problem. To detect a collision, a station must be able to transmit and listen at the same time, but in radio communications, the transmission drowns out the ability of

the station to “hear” a collision. To account for this difference, 802.11 uses a slightly modified protocol, CSMA/CA or the Distributed Coordination Function (DCF)[6]. These protocols attempt to avoid collisions by using explicit packet acknowledgement (ACK), which means an ACK packet is sent by the receiving station to confirm that the data packet arrived.

CSMA/CA works in the following manner: A station wishing to transmit, senses the air, and, if no activity is detected, the station waits an additional, randomly selected period of time and then transmits if the medium is still free. If the packet is received intact, the receiving station issues an ACK frame that, once successfully received the sender, completes the process. If the ACK frame is not detected by the sending station, either because the original data packet was not received intact or the ACK was not received intact, a collision is assumed to have occurred and the data packet is transmitted again after waiting another random amount of time.

Another MAC-layer issue is the “hidden node” problem, in which two stations on opposite sides of an access point can both hear activity from an access point, but not from each other usually due to distance or an obstruction. To solve this issue, 802.11 specifies an optional Request to Send/Clear to Send (RTS/CTS) protocol at the MAC layer. When this feature is in use, a sending station transmits an RTS and waits for the access point to reply with CTS. Since all stations in the network can hear the access point, the CTS causes them to delay any intended transmissions, allowing the sending station to transmit and receive a packet acknowledgement without any chance of collision. Since RTS/CTS adds additional overhead to the network by temporarily reserving the medium, it is typically used only on the largest-sized packets, for which retransmission would be expensive from a bandwidth standpoint.

Finally, the 802.11 MAC layer provides for two other robustness features: CRC checksum and packet fragmentation. Each packet has a CRC checksum calculated and attached to ensure that the data was not corrupted in transit. This is different from Ethernet, where higher-level protocols such as TCP handle error checking. In cases of UDP transmission such as real-time data, there may be potential problems due to

interference or obstruction. Packet fragmentation allows large packets to be broken into smaller units when sent over the air, which is useful in very congested environments or when interference is a factor, since larger packets have a better chance of being received [9]. This technique reduces the need for retransmission in many cases and thus improves overall wireless network performance. The MAC layer is responsible for reassembling fragments received, rendering the process transparent to higher level protocols.

c. Physical Layer

The three physical layers originally defined in 802.11 included two spread-spectrum radio techniques and diffuse infrared specification. The radio-based standards operate within the 2.4 GHz ISM band. These frequency bands are recognized by international regulatory agencies radio operations. As such, 802.11-based products do not require user licensing or special training. Spread-spectrum techniques, in addition to satisfying regulatory requirements, increase reliability, boost throughput, and allow many unrelated products to share the spectrum without explicit cooperation and with minimal interference. The original 802.11 wireless standard defines data rates of 1 Mbps and 2 Mbps via radio waves using frequency hopping spread spectrum (FHSS) or direct sequence spread spectrum (DSSS). FHSS and DSSS are fundamentally different signaling mechanisms and will not interoperate with one another. FHSS divides the 2.4 GHz band into 75 1-MHz subchannels. The sender and receiver agree on a hopping pattern, and data is sent over a sequence of the subchannels. Each conversation within the 802.11 network occurs over a different hopping pattern, and the patterns are designed to minimize the chance of two senders using the same subchannel simultaneously. FHSS techniques lead to a high amount of hopping overhead because the stations and access points must hop often. In contrast, DSSS techniques divide the 2.4 GHz band into 14 22-MHz channels. Adjacent channels overlap one another partially, with three of the 14 being completely non-overlapping. Data is sent across one of these 22 MHz channels without hopping to other channels. To compensate for noise on a given channel, a technique called “chipping” is used. Each bit of user data is transformed into a series of redundant bit patterns called “chips.” The inherent redundancy of each chip combined

with spreading the signal across the 22 MHz channel provides for a form of error checking and correction; the signal can be recovered if it is damaged, in most cases.

A multicarrier scheme that is used heavily in today's WiFi products (WiMAX also) is Orthogonal Frequency Division Multiplexing, as shown in Figure 12, which works well for high-speed, full-duplex wireless transport. It was developed in the 1960s but has gotten a lot of attention recently, because the newer, faster processors can perform the high-speed operations it relies on. OFDM works an intriguing way, squeezing together a collection of modulated carriers, reducing bandwidth requirements but maintaining orthogonality among them to make sure they do not interfere with one another, so they are independent and not interfering. OFDM works by splitting the radio signal into multiple smaller sub-signals that are then transmitted simultaneously at different frequencies to the receiver [1]. OFDM relies on frequency division multiplexing (FDM), which uses multiple frequencies to transmit multiple simultaneous signals in parallel across a facility even if the facility is wireless. Each signal component has its own frequency range, which is then modulated by the data it transports and then demodulated by the receiver, using filters to separate the individual carriers.

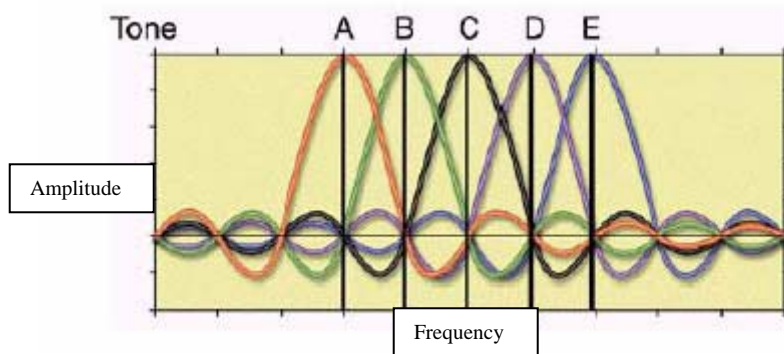


Figure 12. Overlapping OFDM channels (After: [8]).

d. IEEE 802.11 Evolution

The IEEE 802.11 standard has gone through several iterations and improvements throughout its relatively short yet growing lifespan. The evolving nature of this standard is a direct result of the expanding need for higher data rates and security

improvements. As noted in Table 2, it is clear that 802.11 is a powerful standard but is not necessarily designed for higher data rates. Although 802.11n hopes to achieve rates around 350+ Mbps, it may not be sufficient enough to satisfy the demand of video streaming and gaming technologies.

802.11a	<ul style="list-style-type: none"> • Specifies a PHY that operates in the 5 GHz U-NII band in the US - initially 5.15-5.35 AND 5.725-5.85 - since expanded to additional frequencies • Uses Orthogonal Frequency-Division Multiplexing • Enhanced data speed to 54 Mbps • Ratified <u>after</u> 802.11b
802.11b	<ul style="list-style-type: none"> • Enhancement to 802.11 that added higher data rate modes to the DSSS (Direct Sequence Spread Spectrum) already defined in the original 802.11 standard • Boosted data speed to 11 Mbps • 22 MHz Bandwidth yields 3 non-overlapping channels in the frequency range of 2.400 GHz to 2.4835 GHz • Beacons at 1 Mbps, falls back to 5.5, 2, or 1 Mbps from 11 Mbps max.
802.11d	<ul style="list-style-type: none"> • Enhancement to 802.11a and 802.11b that allows for global roaming • Particulars can be set at Media Access Control (MAC) layer
802.11e	<ul style="list-style-type: none"> • Enhancement to 802.11 that includes quality of service (QoS) features • Facilitates prioritization of data, voice, and video transmissions
802.11g	<ul style="list-style-type: none"> • Extends the maximum data rate of WLAN devices that operate in the 2.4 GHz band, in a fashion that permits interoperability with 802.11b devices • Uses OFDM Modulation (Orthogonal FDM)

	<ul style="list-style-type: none"> Operates at up to 54 megabits per second (Mbps), with fall-back speeds that include the "b" speeds
802.11h	<ul style="list-style-type: none"> Enhancement to 802.11a that resolves interference issues Dynamic frequency selection (DFS) Transmit power control (TPC)
802.11i	<ul style="list-style-type: none"> Enhancement to 802.11 that offers additional security for WLAN applications Defines more robust encryption, authentication, and key exchange, as well as options for key caching and pre-authentication
802.11j	<ul style="list-style-type: none"> Japanese regulatory extensions to 802.11a specification Frequency range 4.9 GHz to 5.0 GHz
802.11k	<ul style="list-style-type: none"> Radio resource measurements for networks using 802.11 family specifications
802.11m	<ul style="list-style-type: none"> Maintenance of 802.11 family specifications Corrections and amendments to existing documentation
802.11n	<ul style="list-style-type: none"> Higher-speed standards -- under development Several competing and non-compatible technologies; often called "pre-n" Top speeds claimed of 108, 240, and 350+ MHz Competing proposals come from the groups, EWC, TGn Sync, and WWiSE and are all variations based on MIMO (multiple input, multiple output)
802.11x	<ul style="list-style-type: none"> Mis-used "generic" term for 802.11 family specifications

Table 2. IEEE 802.11 Evolution (After: [4], [6], [8], [9]).

3. IEEE 802.16 and Its Corresponding WiMAX Technology

The growing need for higher data rates has forced researchers and technologists alike to develop better transmission methods with greater efficiency. This has also led to the growth of broadband data communications like never before seen. And the need does not appear to be slowing down anytime soon. It would not be an unrealistic assumption or prediction to propose that in the future there will continue to be a need for higher data rates so long as communications remains a viable part of humanity. It is important to be clear about what is meant by broadband communications. Typically, “broadband” means the capability to deliver significant bandwidth to each user, much higher than narrowband voiceband modems. With International Telecommunications Union (ITU) terminology, the term “broadband” means transmission rates greater than 1.5Mb/s [8]. Broadband Internet access has become a prevalent industry reaching 100 million homes and some 5 million businesses just in the United States [1].

There are generally four major technologies for broadband Internet access. They are: DSL, cable, wireless, and optical fiber communications. DSL and cable occupy most of the market now but with the expansion of wireless access, specifically cellular technology and WiMAX, it is expected that broadband wireless access (BWA) systems will become a competitive technology. If BWA systems are to compete with DSL and Cable, their market growth will be significant for several reasons. First, BWA systems are capable of delivering significantly higher data rates than DSL or cable. DSL can deliver up to 6Mb/s at distances up to 18,000 feet, hence the customers’ needs to be close to the telephone company’s central office. Not everyone in North America has DSL or cable access, not to mention the global implications of access.

The IEEE 802.16 Working Group was formed in August 1998 with a primary purpose of delivering network access to enterprise and residence customers via a secure broadband wireless facility. The first standard was published in early April 2002 and was known as IEEE 802.16-2001. There have been several iterations since that will be discussed later in this chapter. The standard is quite precise in its description of the intended capability. It specifies that network access will be achieved by means of external

antennas connected to central base stations, offering a connectivity alternative to wired broadband options. Since wireless solutions can provide services to a large geographic without the need to spend inordinate quantities of capital expense and operating expense in the process, it may turn out to be a less expensive service delivery option than its wired predecessors and may become the solution for broadband delivery in areas that are challenged by distance, population density, or topologic difficulties.

Worldwide Interoperability for Microwave Access (WiMAX) is a wireless communication system that allows computer and workstations to connect to high-speed data networks (such as the Internet) using radio waves as the transmission medium with data transmission rates that can exceed 75 Mbps for each radio channel [10]. WiMAX will be used for both fixed and mobile broadband wireless access. It is a system that is primarily used as a wireless metropolitan area network (WMAN). WMANs can provide broadband data communication access throughout an urban or city geographic area. WMANs are used throughout the world and their applications include consumer broadband wireless Internet services, interconnecting lines, and transport of digital television services. The IEEE 802.16 system was designed for fixed location Nomadic service. Nomadic service is defined as providing communication services to more than one location for the subscriber. However, nomadic service typically requires the transportable communication device to be fixed in location during the usage of communication service.

For mobile services, the IEEE 802.16e-2005 version was developed. This specification adds mobility management, extensible authentication protocol (EAP), handoff (call transfer), and power saving sleep modes. WiMAX has several different physical radio transmission options which allow WiMAX systems to be deployed in areas with different regulatory and frequency availability requirements.

Once the wireless signal has been received at the building that houses the customer, the customer connects its preexisting in-building network to the wireless access point. In the future, however, research is being conducted to allow the subscriber station to connect directly to the 802.16 signal since the chipsets ultimately will be cheap enough to install in laptops and even personal digital assistants (PDAs). In effect, the base station

will connect to the laptop or PDA by relying on a single MAC layer to “erase” the problems associated with different physical layers, thus ensuring adequate quality of service (QoS) and viable connectivity. As later versions of IEEE 802.16 emerge and become ratified, most notably 802.16e-2005, mobility will become a viable usage option.

a. IEEE 802.16 Architecture

The IEEE 802.16 standard provides for two main distinct uses of this technology, point to point (PTP) and point to multipoint (PMP), as shown in Figure 13. PTP connections may be independent from all other systems or networks. A PMP system allows a radio system to provide services to multiple users. WiMAX systems consist of:

- Subscriber stations (SS) – receive and convert radio signals into user information
- Base stations (BS) – this is the cell site. Base stations convert signals from SSs into a form that can be transferred into the wireless network and conversely.
- Interconnecting switches and transmission lines – transfer signals between BS and other systems (such as PSTN or the Internet)
- Databases – similar to cellular network structure, these are collections of data that is interrelated and stored in memory. These databases usually contain subscriber information, equipment configuration, feature lists and security codes.

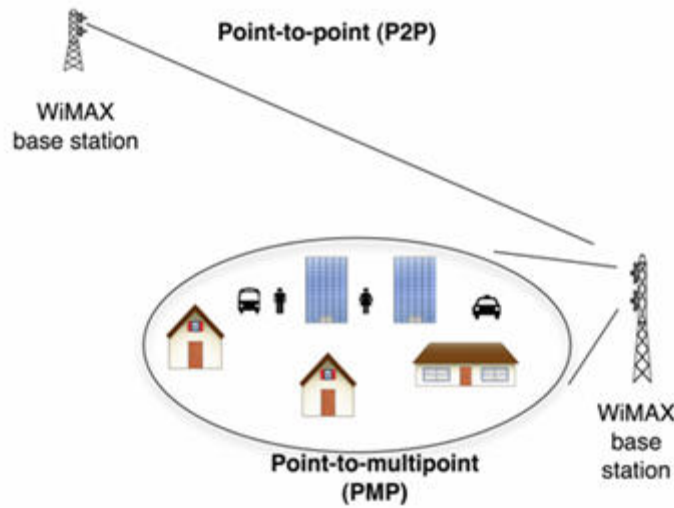


Figure 13. Description of PTP and PMP (From: [9]).

The original 802.16 industry specification was for a line of sight system that would operate in the 10GHz to 66 GHz radio spectrum. Not long after, there was a growing need to operate in the lower ranges, namely in the 2GHz to 11GHz bands, because they are less susceptible to physical obstacles [1]. The 802.16a specification was developed to address operation in the new spectrum ranges [8]. Recently, several different revisions have been developed to address an operating range between 2GHz and 66GHz that allow for mobility and higher data rates. More importantly, the new revisions allow for operation in both line-of-sight (LOS) and non-line-of-sight (NLOS) environments as shown in Figure 14. These versions will be discussed in greater detail later in this chapter.

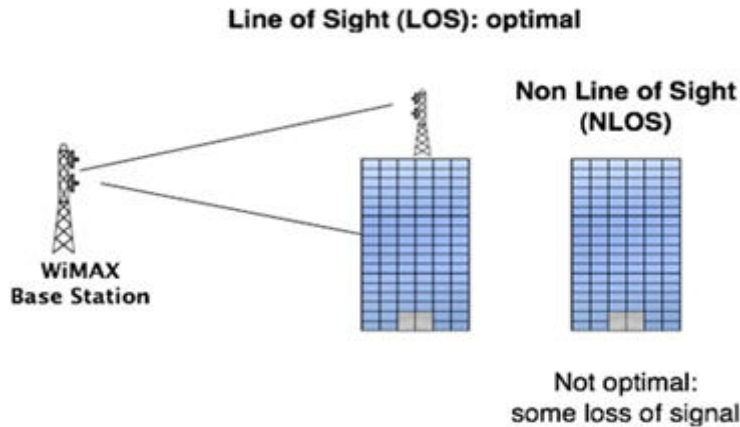


Figure 14. LOS vs. NLOS (From: [9]).

b. Data Link Layer: 802.16 MAC Layers and Sublayers

Media Access Control (MAC) controls access to whatever physical transmission medium is being used by the device that wishes to transmit. The functionality of the MAC layer is usually “hard-coded” into the device and always includes a unique address (the MAC address) that identifies the machine that houses the network adapter. The 802.16 MAC protocol was designed with a number of required characteristics in mind. First, it was created to handle the demands of PTMP broadband wireless applications. Within that definition, it also was designed to provide very high, full-duplex (uplink and downlink) bandwidth, with that bandwidth being capable of being parceled out across a collection of channels with scores of users in each channel. Additionally, users place varying demands on the channels they are allocated; this translates into a requirement to support traditional voice and data services as well as packet-based Voice over Internet Protocol (VoIP) and other Internet Protocol (IP) data services. The MAC, then, must be able to handle the demands of both constant bit rate (CBR) and bursty traffic and must support variable QoS as demanded by the user community.

The MAC layer consists of three sublayers – convergence sublayer, common part sublayer, and security sublayer as shown in Figure 15. The MAC includes a

convergence sublayer to better handle the higher-layer protocols placed above the MAC. The central part of the MAC is the common part sublayer. It handles channel access, connection establishment and maintenance, and QoS. The third sublayer is the security sublayer, providing authentication, secure key exchange, and secure data exchange. The security sublayer is out of the scope of this thesis. The convergence sublayer is not a physical, but rather a logical interface since it is a separate part of the MAC. The common part sublayer is the central part of the IEEE 802.16 MAC. It defines the multiple-access mechanism. In the downlink for the 802.16d, the base station is the only transmitter that is operating. Therefore, it does not have to coordinate its transmissions with other stations. The base station broadcasts to all stations. Stations check the address in the received messages and retain only those addressed to them. In the uplink direction, the user stations share the channel. These details and the advantages/disadvantages of the MAC will be discussed further in Chapter IV.

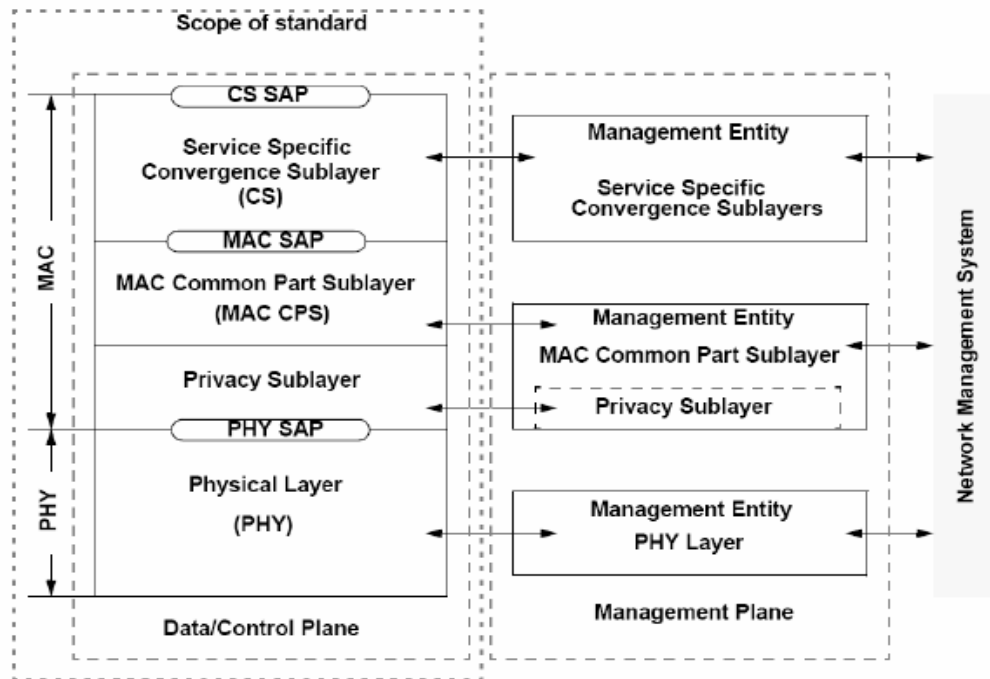


Figure 15. Protocol Layering of 802.16 (From: [11]).

c. IEEE 802.16 Physical Layer

Generally, physical layers have two sublayers: a transmission convergence sublayer and a Physical Medium Dependent (PMD) sublayer. Each PMD sublayer may have its own definition of a particular transmission convergence sublayer. In addition, a physical layer may be accompanied by a physical layer management entity. The IEEE 802 standards do not specify the exact functions of the management entity; those functions are left up to the vendors. This management entity generally is responsible for such functions as gathering of layer-dependent status and interaction with general system management.

IEEE 802.16 defines several physical layers, for business and other purposes. The main benefit of this is that it allows vendors the ability to implement whichever one they want. These vendors are then able to experiment and conduct research to see which particular layers operate at an optimal level under certain criteria. As was discussed, there are two primary operating ranges for 802.16, the 2 to 11 GHz range and the 10 to 66 GHz range. Both operate quite differently with different purposes.

IEEE 802.16 and its corresponding WiMAX technology offer two completely different implementation options. They are: line of sight (LOS) and non-line of sight (NLOS). These options actually lend themselves to a variety of different uses for this technology. The reason lies within the physics behind the options themselves. The first is a line of sight (LOS) option. These systems will operate in the 10 to 66 GHz frequency range. The idea is that in this scenario a fixed antenna, typically a small dish, is oriented so that it can “see” the antenna mounted on a remote WiMAX tower. This is a very reliable service option because it relies on an uninterrupted microwave connection between two antennas. Since it operates in the higher ranges of the frequency band, it has greater available bandwidth but shorter range. Notwithstanding the facts that since these are shorter distances between end-points there is a chance for reduced interference. LOS systems in general can operate at distances up to about five miles, and this provides a very rough service footprint of about 75 square miles [12]. With high-end antennas, it is

quite possible to transmit as far as 30 miles to one of the high-end routers on the market today [1]. However, increased distances generally mean decreased bandwidth.

The characteristics of outdoor wireless channels can be quite different. In wireless communications over 10GHz, the multipath components will be absorbed rather than reflected. The energy on these LOS components that end up reaching the receiver are quite small. This is why they must be within LOS and not travel very large distances because the energy lessens with range and interference.

The physical layer for operation between 10 GHz and 66 GHz must allow for flexible spectrum usage and support both time division duplexing (TDD) and frequency division duplexing (FDD). The burst transmission format of the PHY is framed so that it supports adaptive burst profiling in which transmission parameters, including the modulation and coding schemes, can be adjusted to support both the physical and communications requirements of each subscriber station (SS) on a frame-by-frame basis. It also uses adaptive modulation which means that systems communicate using multiple burst profiles.

There is a further distinction within the physical layer: the uplink physical layer and the downlink physical layer. These have completely different functionality obviously, and therefore different parameters. The uplink physical layer is based on a combination of time division multiple access (TDMA) and demand-assigned multiple access (DAMA). The TDMA part is divided into a number of time slots. The downlink channel is time division multiplexed (TDM), with the information for each subscriber station multiplexed onto a single stream of data and received by all subscriber station within the same sector.

Non line of sight 802.16 systems operate in a much lower frequency range (2 to 11 GHz) and are therefore less susceptible to physical obstacles. These systems rely on a signal-encoding scheme already mentioned in this chapter known as OFDM. Ultimately, WiMAX technology will facilitate the deployment of what has become to be known as Global Area Network (GAN). GAN, which is documented heavily in IEEE standard 802.20, defines an environment in which a subscriber can roam the county,

perhaps the world, and stay connected regardless of their location [8]. This ties into a concept where every user is connected anytime, anywhere, always-on, and there is access to content on the user's terms, not those of the networks. Clearly, IEEE 802.16 and its WiMAX technology will play a key role in the deployment of that capability.

The 2-11 GHz band provides a physical environment where, due to the longer wavelength, line of sight is not necessary and multipath may be significant[1]. The channel bandwidths in this frequency range tend to fall between the range of 1.5 MHz and 14 MHz [1] Since this is for NLOS services, there will be additional functionality in the physical layer. This functionality will include but not be limited to: power management techniques, interference mitigation/coexistence, and smart antennas.

Both single-carrier modulation and multiple-carrier modulation can be used. Generally speaking, the goal of a modulation technique is to transfer data over a prescribed channel bandwidth, within transmit power, reliability, and receiver complexity constraints. Since, there are both licensed and unlicensed bands in this frequency range, the IEEE standard accounts for them both. All frequency layers in this range have some common characteristics. FDD, Half-FDD, and TDD modes provide for bidirectional operation, except for operation in the license-exempt band, where provision is made for TDD operation only.

d. IEEE 802.16 Evolution

The IEEE 802.16 standard is still being actively developed by the IEEE 802.16 working group. There are many revisions still in the planning stages. Currently, the two versions that are being exploited are 802.16-2004 and 802.16e-2005. IEEE 802.16-2004 is the fixed version while the e-version also handles the mobile piece. Both use OFDM, but 802.16e-2005 uses OFDMA due to its mobile piece. Actual gear and products have started rolling out the past few years, with actual NIC cards being introduced into the market January 2007 [2]. In the next couple years, more and more products will be showing up for commercial use as more and more corporations are looking to incorporate this technology into their communications systems. Future uses

and investments of 802.16 will be covered in a later chapter. Table 3 shows the complete list of versions including those still under development.

802.16.1	<ul style="list-style-type: none"> • Original work began in 2001 • 10-66 GHz frequency range (LOS) • Anticipated speeds up to 134 Mbps
802.16.2	<ul style="list-style-type: none"> • Soon after work began on 802.16.1, noticed need to minimize interference between coexisting WMANs
802.16a	<ul style="list-style-type: none"> • Developed for licensed and unlicensed bands between 2-11 GHz (NLOS) • Delivered a point to multipoint capability • OFDM and OFDMA • Data speeds up to 75 Mbps, low latency, efficient use of spectrum space • Maximum range is 30 miles with throughput degradation • Approved in January 2003; intended to provide “last mile” fixed broadband access
802.16b	<ul style="list-style-type: none"> • Specifically designed for 5-6 GHz range
802.16c	<ul style="list-style-type: none"> • Developed for RF bands in 10-66 GHz range • Concerned with detailed system profiling, performance evaluation, and testing
802.16-2004	<ul style="list-style-type: none"> • Also known as 802.16d or Fixed WiMAX • Supersedes previous versions of 802.16 • Utilizes OFDM 256-FFT (Fast Fourier Transform) system profile • Supports both TDD and FDD services • Launched in 2003 and concluded in 2004

802.16e-2005	<ul style="list-style-type: none"> • Also known as mobile WiMAX • Enhancements include better support for Quality of Service (QoS) and the use of Scalable OFDMA
802.16f	<ul style="list-style-type: none"> • Management information Base
802.16g	<ul style="list-style-type: none"> • Management Plane Procedures and Services
802.16h	<ul style="list-style-type: none"> • Improved Coexistence Mechanisms for License-Exempt Operation
802.16i	<ul style="list-style-type: none"> • Mobile Management Information Base
802.16j	<ul style="list-style-type: none"> • Multihop Relay Specification
802.16k	<ul style="list-style-type: none"> • Bridging of 802.16
802.16m	<ul style="list-style-type: none"> • Advanced Air Interface. Data Rates of 100Mbps for mobile applications and 1Gbps for fixed applications, cellular, macro and micro cell coverage, with currently no restrictions on the RF bandwidth • Anticipated completion of standard by Sep 2008

Table 3. IEEE 802.16 Evolution (From: [1], [5], [6], [8]).

Clearly, wireless communications will continue to grow and develop as the demand for mobility becomes an important feature in the telecommunications industry. Wireless also has the added benefit of being a cheaper alternative to wired communications. These two features of wireless will enable it to become a more viable solution to many of the challenges facing the communications industry. One of these challenges revolves around the issue of multicasting data in a network. This important challenge will be addressed in the next chapter as well as problems with existing technologies and its handling of such delivery techniques.

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III. MULTICAST IN 802.11

This chapter focuses on two main parts. The first section describes multicast delivery while the second part describes multicast in IEEE 802.11 and issues and challenges resulting from this.

A. MULTICAST DELIVERY

1. Delivery Basics

There are generally three different types of communication that can occur in Layer 3 IPv4 routing protocols. These are: unicast, broadcast, and multicast. IPv6 has introduced a new address known as anycast. Anycast addressing simply routes the particular packet to be delivered to any one of a group of hosts. Figure 16 represents what an anycast addressing scheme may look like. In unicast routing a single source node sends a packet to a single destination node. In broadcast routing, the network layer provides a service of delivering a packet sent from a source node to all other nodes in the network. Multicast routing enables a single source node to send a copy of a packet to a subset of the other network nodes.

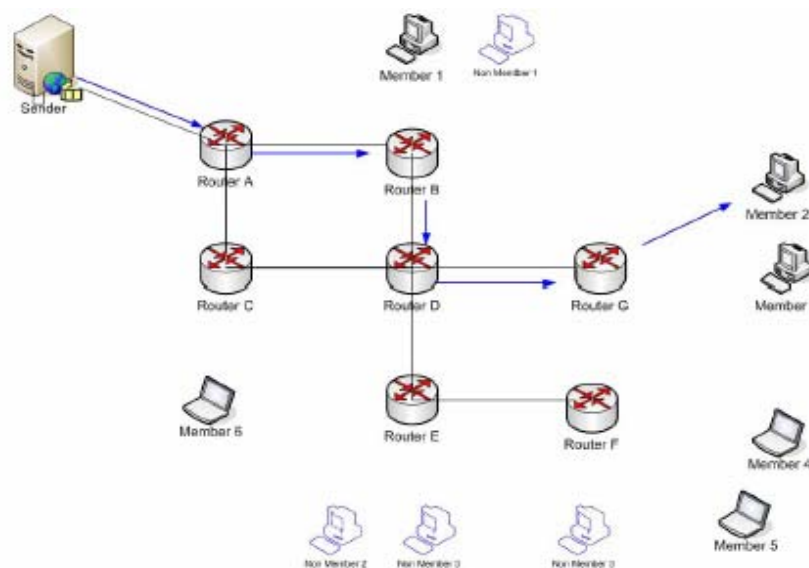


Figure 16. Anycast Routing Example (From: [13]).

Although unicast routing seems to be the simplest form of routing, it still has complexities and demands placed upon it which have different outcomes depending on what parameters one sets upon it. An example of unicast routing to multiple destinations is shown in Figure 17. There are many different routing protocols that support unicast routing. One way to classify these protocols, or algorithms, is according to whether they are global or decentralized. A global routing algorithm computes the least-cost path between a source and destination using complete, global knowledge about the network. Essentially, the algorithm takes the connectivity between all nodes and all link costs as inputs. Usually every node will transmit its own data to every other node in the system. The algorithm takes this information, runs it through its algorithm and then will have complete knowledge of the network connectivity and costs associated with it. In practice, algorithms with global state information are often referred to as link-state algorithms, since the algorithm must have knowledge about the state of each individual link in the network.

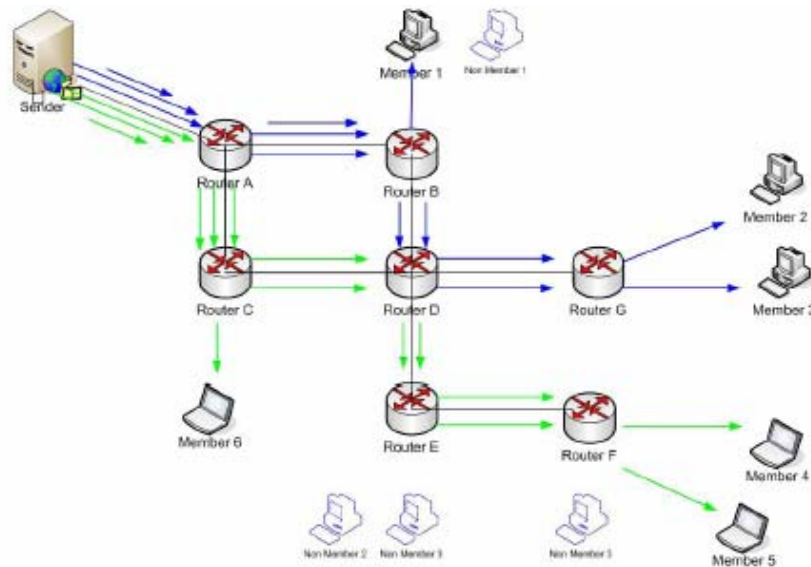


Figure 17. Unicast Routing to Multiple destinations (From: [13]).

In a decentralized routing algorithm, the calculation of the least-cost path is carried out in an iterative, distributive manner. No node has complete information about the costs of all network links. Instead, each node begins with only those costs associated

with its immediate neighbors. Then through an iterative process of calculation and then exchange of information with its neighbors, a node can calculate the least-cost path to a destination or set of destinations. One particular example of a decentralized routing algorithm is a distance vector (DV) algorithm [4]. It is known as this because each node maintains a vector of estimates of the costs to all other nodes in the network. A DV algorithm is iterative, asynchronous, and distributed. It is distributed in that each node receives some information from one or more of its directly attached neighbors, performs a calculation, and then distributes the results of its calculation back to its neighbors. It is iterative in that this process continues on until no more information is exchanged between neighbors. The algorithm is asynchronous in that it does not require all of the nodes to operate simultaneously with one another. Both algorithms may be present in a system and while there are advantages and disadvantages between the two, that sort of information is out of the scope of this thesis.

A second form of routing is broadcast routing, as shown in Figure 18. Broadcast routing as stated previously, is when a single node wishes to get information to every other node in the network. There are several different methods available to achieve this. The first of which is the N-way –unicast approach in which the sending node sends a separate copy of the packet to each destination. So, given N destination nodes, the sender is responsible for making N copies, addresses each copy to a different destination, and then transmits the N copies to the N destinations using unicast routing. This is a highly inefficient method as it requires tremendous work on the sender's part and ties up the links with duplicate transmissions.

Another technique for achieving broadcast is a flooding approach in which the source node sends a copy of the packet to all of its neighbors. There are two types of flooding approaches: controlled and uncontrolled flooding. In uncontrolled flooding, the node receives a broadcast packet, duplicates the packet and forwards it to all of its neighbors regardless of whether or not they have received it already. This could potentially result in a broadcast storm, which would eventually render the network useless. Controlled flooding aims to judiciously choose when to flood a packet and when not to flood a packet. A final approach is known as a spanning-tree broadcast. Spanning-

trees are defined as it creates a spanning tree within a mesh network of connected layer-2 bridges, and disables the links which are not part of that tree, leaving a single active path between any two network nodes [4]. In this approach, every node will receive only one copy of the broadcast packet. This is a feature that even controlled flooding cannot guarantee as some nodes will still receive duplicate packets. Spanning trees are an important feature of multicast as well and will be discussed further in the next section.

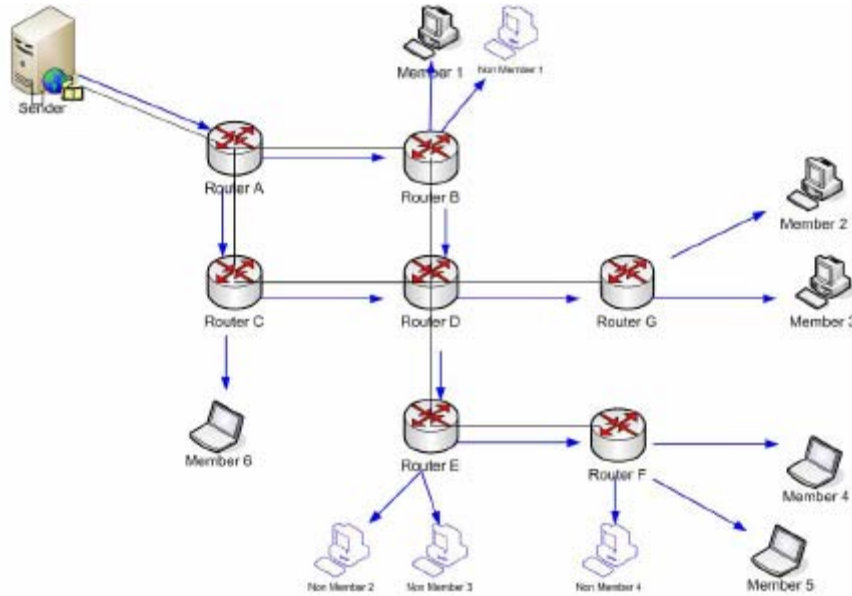


Figure 18. Broadcast Routing Example (From: [13]).

2. Multicast in IP

There are instances, as one can imagine, that one would wish to transmit to a group of nodes not just one but not all the nodes in a network; for this instance, multicast service is ideal because it allows for a multicast packet to be delivered to a subset of network nodes. Figure 19 describes what a multicast group may look like, and the optimization of as few of transmissions as possible. A number of emerging network applications requires the delivery of packets from one or more senders to a group of receivers. These applications include bulk transfer (software upgrades), streaming continuous media, shared data applications, data feeds, Web cache updating, and interactive gaming [14]. In multicast, there exist two general challenges. The need to

identify the receivers of a multicast packet (multicast group) and how to address a packet sent to these receivers. A multicast packet uses address indirection to address the first challenge. This is when a single identifier is used for the group of receivers, and a copy of the packet that is addressed to the group is delivered to all of the multicast receivers associated with that group. To address the second challenge of addressing a packet sent to a multicast group, the answer lies in the receiver rather than the sender. A host, who wants to join a particular multicast group, simply sends a message to its router that it wants to join this group. Its router will propagate that information to other Internet routers, who will in turn forward as needed to its attached router. The key is that the receiver must join, in a sense, a particular group and then the multicast routing algorithm in place will assure that the packets are delivered.

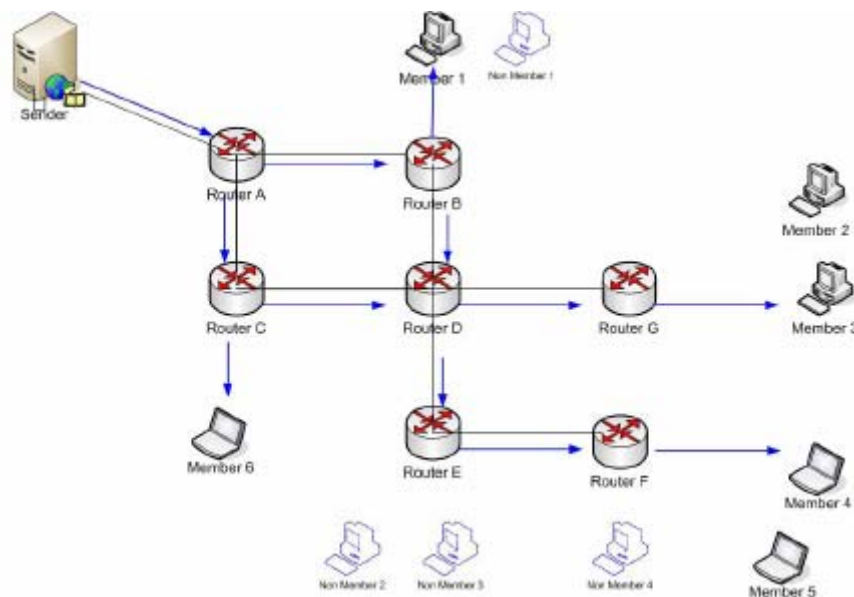


Figure 19. An example of a Multicast Routing Scenario (From: [13]).

The goal of multicast routing is to find a tree of links that connects all of the routers that have attached hosts belonging to the multicast group. Multicast packets will then be routed along this tree from the sender to all of the hosts belonging to the multicast tree. The tree may contain routers that do not have attached hosts belonging to the

multicast group as indicated with Router C and Router D in Figure 19. In practice there are two approaches for determining the multicast routing tree. The first is using a group-shared tree. This is based on building a tree that includes all edge routers with attached hosts belonging to the multicast group. In practice, a center-based approach is used to construct the multicast routing tree, with edge routers with attached hosts belonging to the multicast group sending (unicast) join messages addressed to the center node. The second approach to determining the multicast routing tree is a source-based tree. While group-shared tree multicast routing constructs a single, shared routing tree to route packets from all senders, source-based trees construct a multicast routing tree for each source in the multicast group. Two multicast routing protocols used in the Internet are: Distance-Vector Multicast Routing Protocol (DVMRP) and Protocol-Independent-Multicast (PIM) routing protocol. These are prevalent but a detailed analysis of them is out of the scope of this thesis [4].

B. IP MULTICAST IN 802.11

1. Description of Problem

There is a growing demand for networks that can handle large data at a very high rate due to the applications that are becoming more and more desirable. All forms of wireless and wired networks need to be developed further to account for this need. With IEEE 802.11 cornering the market on wireless LANs, there has been much research into developing this medium to account for the increased rate demand. The multicast multimedia delivery service is a solution to this problem. It allows for delivery to a subset or group of nodes at higher rates because there is less need to overuse the network to facilitate the delivery of packets. For example, multicasting video instead of streaming individually each video flow results in a much more efficient use of the shared wireless medium. Most, if not all, are time-sensitive applications and require UDP transmission. UDP transmission is a transport layer protocol (Layer 4) and does not have built-in reception notification like TCP does. So it is a connectionless protocol and can be thought of as a “fire and forget” protocol.

The multicast multimedia delivery service on WiFi compliant devices is still in its early stages of development. The real difficulty is the IEEE 802.11 MAC protocol, and in particular, the absence of feedback mechanism when multicast is used [15]. There has been much research to solve this issue with WiFi and although it has proved to be helpful, it does not completely satisfy the problem. The reason is that WiFi was not developed with multi-media applications in mind, so it has limitations built into it.

IEEE 802.11 wireless LANs are one of the fastest growing network technologies in the wireless communications field. Today, most of our personal digital assistants (PDAs) and laptops by default include a WiFi interface. There is also a growing desire for multimedia applications to be delivered to these devices. The question becomes, how do we get these applications to their destinations in a timely manner while utilizing the bandwidth for maximum throughput? Multicasting, as has already been discussed is part of the solution, but it in itself will not solve it completely.

There are severe issues that result when multicasting using WiFi products. The problem is the MAC layer sends multicast packets in open-loop as broadcast packets [3]. This means there will be no acknowledgements of receipt of the packets. This open-loop transmission mechanism causes three problems:

- a. Since there is no feedback mechanism, it is not possible to adapt the contention window according to the network state, so multicast flows achieve a higher priority than concurrent unicast flows. Essentially, they take over the network and collapse it.
- b. It is not possible to adapt the physical transmission rate to the channel characteristics, so the packets are broadcast over the wireless medium at one of the rates included in the basic rates set.
- c. Lastly, there is no way to retransmit lost packets at the MAC layer, and definitely not at the IP or transport (UDP) layers, so the transmission is more lossy than unicast flows, which degrades this application's performance [3].

When experiments were run, the most severe problem is that contrary to unicast flows, legacy multicast flows cannot adapt their to access the channel according to the network load. This leads to severe unfairness between multicast and unicast flows and can even cause network collapse.

2. Further Research on Multicast in IEEE 802.11

There has been a significant amount of research on this topic which has led to many different solutions that have been tested in simulations. Table 4 shows a list of a few of these solutions. The first alternative centers on the idea of having a leader-based multicast mechanism [3]. It proposes that one of the receivers send acknowledgement frames back to the sender. As with regular unicast transmissions, the multicast can use a PHY rate selection mechanism conducive for this type of traffic. It also suggests that lost packet can be retransmitted as is the case for unicast flows. Dujovne & Turletti's paper [3] also contends that the leader-based approach provides fairness with other unicast flows because the same algorithm is used to adapt the contention window. Experimentation was done by the authors and they noticed an increase in throughput without bringing the network down. This increase was measured against total bytes as well as against a combination of both unicast and multicast traffic. However, the approach did not solve the issue of dynamically selecting the leader.

Solution	Description and Issues
Leader-based multicast mechanism [3]	<ul style="list-style-type: none"> Select one of the receivers to send acknowledgement frames back to the sender Experimentation revealed significant improvement but no selection algorithm in place
Layered-encoding scheme [14]	<ul style="list-style-type: none"> Hybrid error correction Addressed theoretically optimization of video transmission but assumed uniform distributed packets
Contention window adaptation [16]	<ul style="list-style-type: none"> Dynamically adapt the window according to the number of competing stations in the WLAN Performance is evaluated using a multicast fairness index Simulations assume a perfect network with no transmission errors. In practice, contention window size depends on collision and transmission errors; performance results are not realistic
Modify MAC layer [17]	<ul style="list-style-type: none"> Proposed different protocols to modify the MAC layer to enable the RTS/CTS option in multicast mode One receiver, called the leader, responds with a CTS or an ACK Not scalable, only convenient for low mobility wireless stations
MAC layer improvements [3]	<ul style="list-style-type: none"> Allows for layered video transmission Leader is selected for each heterogeneity of receivers to send ACK frames Disadvantage is severe shadowing effects

Table 4. Proposed solutions to Multicast in 802.11 challenges.

Most of these solutions suggested require complete overhaul of the WiFi standard, most notably the MAC layer where there is a need for a sub-layer to address these issues. However, the 802.16 standard already has a MAC sub-layer in place to offset these issues. IEEE 802.16 and its corresponding WiMAX technology, was already designed to handle this issue and would be a better medium to handle these sorts of applications. This will be discussed in the next chapter which provides an in-depth look at the MAC layer of 802.16 as well as potential applications for the new WiMAX technology.

IV. DETAILED ANALYSIS OF MULTICAST IN 802.16 AND POTENTIAL APPLICATIONS FOR WIMAX

The first section of this chapter describes multicast in 802.16 while the second section describes potential applications for the emerging technology.

A. MULTICAST DELIVERY BETTER SUITED FOR IEEE 802.16 AND WIMAX

One of the goals of this chapter and ultimately this thesis is to show that the IEEE 802.16 standard and its associated technology is a better alternative for IP multicast desired applications than WiFi. This, obviously is an emerging technology and has been developed with the concepts of higher data rates, quality of service (QoS), increased ranges, and multicast to name a few. It is this insurance of QoS which also allows for 802.16 to be a better alternative than 802.11 for multicast applications. The reason why this standard is better for multicast and its corresponding technologies lies in the properties of the MAC layer and its sublayers. A detailed analysis of the MAC layer will be presented to show how this enables multicast as well as addresses the challenges which IEEE 802.11 failed to overcome as noted in the previous chapter.

1. MAC Layer

As noted previously, the primary task of the MAC layer is to provide an interface between the higher transport layers and the physical layers. In a network, the purpose of the PHY layer is to reliably deliver information bits from the transmitter to the receiver using the physical medium such as radio frequency, light waves or copper wires. Usually, the PHY layer is not informed of QoS requirements and is not aware of the nature of the application such as VoIP, HTTP, or FTP. The PHY layer can be thought of as a pipe responsible for information exchange over a single link between a transmitter and receiver [18]. The MAC then is responsible for controlling and multiplexing various such links over the same medium. The WiMAX MAC is designed from the ground up to

support very high peak bit rates while delivering ATM compatible QoS. Some of the important functions of IEEE 802.16's MAC layer are the following [2]:

- Segment or concatenate the SDUs (service data units) received from higher layers into the MAC PDU (protocol data units), the basic building block of MAC layer payload.
- Select the appropriate burst profile and power level that is to be used for the transmission of MAC PDU.
- When ARQ (automatic repeat request) is used, the MAC layer is also responsible for the retransmission of MAC PDUs that were not received correctly by the receiver when they were properly addressed and routed.
- QoS control and priority handling of MAC PDUs belonging to different data and signaling bearers.
- Scheduling of MAC PDUs over the PHY resources.
- Providing support to the higher layers for mobility management.
- Security and key management.
- Power saving mode and idle mode operation.

The MAC layer takes packets from the upper layer – called MAC Service Data Units (MSDU) – and organizes them into MAC Packet Data Units (MPDU) for transmission over the air. Received transmissions will just do the same thing in reverse order. It also uses a variable length MPDU, and offers a lot of flexibility to allow for their efficient transmission. For example, multiple MPDUs of same or different lengths may be aggregated into a single burst to save PHY overhead. Also, multiple MSDUs from the same higher layer service may be concatenated into a single MPDU to save MAC header overhead. Conversely, large MSDUs, may be fragmented into smaller MPDUs, and sent across multiple frames [2]. As shown in Figure 20, the MAC layer is divided into three distinct components, namely the service specific convergence sublayer (CS), the common

part sublayer, and the security sublayer. The focus of part of this chapter will be on the first two. It is within those two, which allow for QoS as well as a chance for error correction.

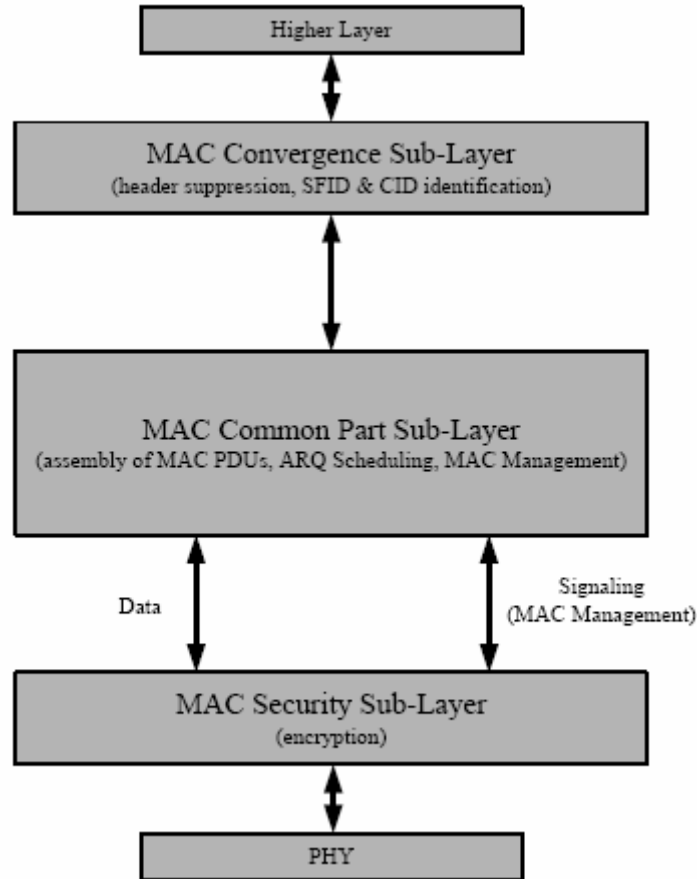


Figure 20. Schematic Representation of MAC Layer (From: [2]).

In WiMAX, the MAC layer at the base station is fully responsible for allocating bandwidth resources to all users, both in the uplink and downlink. The only time the subscriber station (SS) has some control over bandwidth allocation is when it has multiple sessions or connections with the base station (BS). For that scenario, the BS allocates bandwidth to the SS, and it is up to SS to partition it amongst its connections or applications. All other scheduling on both the downlink and uplink is done by the BS. This has a huge advantage over 802.11, where, since that standard uses a contention-based service, certain applications, unicast especially, become squeezed out of the

network. IEEE 802.16, with its time-sharing services (QoS), enables all users and all applications to have sufficient resource capability. Additionally, there are QoS options available where each network can be designed according to the traffic they are most likely to carry.

2. Quality of Service (QoS) in 802.16

Quality of Service is a fundamental part of the WiMAX MAC layer design. It is also been noted that WiMAX borrows some of its QoS design from the cable modem standard [19]. Strong QoS control is achieved by using a connection-oriented MAC architecture. This is part of the reason that multicast applications will fit in better because they use UDP as their transport layer, which is a connectionless protocol. So, essentially this will fill in for the inefficiencies from UDP and time-sensitive applications. All downlink and uplink connections are controlled by the serving base station. Before any data transmission happens, the BS and the SS establish a unidirectional logical link called a connection between the two MAC layer peers. Each connection is identified by a connection identifier (CID), which serves as a temporary address for data transmissions over the particular link. WiMAX also defines a concept of a service flow. A service flow is a unidirectional flow of packets with a particular set of QoS parameters, and is identified by a service flow identifier (SFID). Both the CID and SFID are noted in the convergence sublayer as shown in Figure 20. The QoS parameters could include traffic priority, maximum sustained traffic rate, maximum burst rate, minimum tolerable rate, scheduling type, ARQ (automatic repeat request) type, maximum delay, tolerated jitter, etc. Service flows could be handled by a network management system, or created dynamically through defined signaling mechanisms in the standard. The BS is responsible for issuing SFID and mapping it to a unique CID.

To support a wide variety of applications, WiMAX defines several scheduling services that should be supported by the base station MAC scheduler for data transport over a connection. A scheduling service uniquely determines the mechanism used by the network to allocate uplink and downlink transmission opportunities for the PDUs. The five scheduling services defined are as follows [9]:

- **Unsolicited Grant Service (UGS):** The UGS is designed to support real-time service flows that generate fixed-size data packets on a periodic basis, such as T1/E1, and VoIP. UGS offers fixed-size grants on a real time periodic basis, and does not need the SS to explicitly request bandwidth. This eliminates the overhead and latency associated with the bandwidth request process.
- **Real Time Polling Services (rtPS):** The rtPS is designed to support real-time services that generate variable size data packets on a periodic basis, such as “moving pictures experts group” (MPEG) video [9]. In this service class the BS provides unicast polling opportunities for the SS to request bandwidth. The unicast polling opportunities are frequent enough to ensure that latency requirements of real time services are met. This service requires more request overhead than UGS, but is more efficient for a service that generates variable size data packets or has a duty cycle less than 100%.
- **Non Real Time Polling Services (nrtPS):** nrtPS is very similar to rtPS with the exception that SS can also use the contention based polling in the uplink to request for bandwidth. In nrtPS the SS is allowable to have unicast polling opportunities, but the average duration between two such opportunities are on the order of few seconds, which is large compared to rtPS. All the SSs belonging to the group can request resources during the contention based polling opportunity, which can often result in collisions and additional attempts.
- **Best Effort Services (BE):** The SS uses only the contention-based polling opportunity to request bandwidth. The BE scheduling service provides very little QoS support and is only applicable for services that do not have strict QoS requirements. Data is sent whenever resources are available and not required by any other scheduling service classes.

- **Extended Real Time Polling Service (ertPS):** ertPS is a new scheduling service introduced with the IEEE 802.16e-2005 standard that builds on the efficiencies of the UGS and rtPS. In this case periodic UL allocations are provided for a particular SS, which can either be used for data transmission or for requesting additional bandwidth. These features allow the ertPS to accommodate data service whose bandwidth requirements change with time. Note that in the case of UGS, unlike ertPS, the SS is allowed to request additional bandwidth during the UL allocation for only non-UGS related connections [9].

Table 5 summarizes the five defined service types.

Service Flow Designation	Defining QoS Parameters	Application Examples
Unsolicited Grant Request (UGS)	Maximum Sustained Rate Maximum Latency tolerance Jitter Tolerance	Voice over IP (VoIP) without silence suppression
Real Time Packet Service (rtPS)	Minimum Reserved Rate Maximum Sustained Rate Maximum Latency Tolerance Traffic Priority	Streaming Audio and Video, MPEG
Non-Real Time Packet Service (nrtPS)	Minimum Reserved Rate Maximum Sustained Rate Traffic Priority	File Transfer Protocol
Best Effort Service (BE)	Maximum Sustained Rate Traffic Priority	Web browsing, data transfer
Extended Real-Time Packet Service (ErtPS)	Minimum Reserved Rate Maximum Sustained Rate Maximum Latency Tolerance Jitter Tolerance Traffic Priority	VoIP with silence suppression

Table 5. Service Flows supported in WiMAX (From: [2]).

These service flows allow for the classification of traffic and enables an efficient network designed to accommodate all different types of traffic. One of the problems with 802.11 with regards to multicasting was that it tended to squeeze out unicast traffic and ultimately render the network useless. Service flows are a great solution to this problem.

Though WiMAX does not define the operations of the scheduler, it does define several parameters and features that facilitate the implementation of an effective scheduler. Examples of these include:

- Support for a detailed parametric definition of QoS requirements, and a variety of mechanisms to effectively signal traffic conditions and detailed QoS requirements in the uplink.
- Support for three dimensional dynamic resource allocation in the MAC layer. Resources can be allocated in time (time slots), frequency (subcarriers), and space (multiple antennas) on a frame-by-frame basis.
- Support for fast channel quality information feedback to enable the scheduler to select the appropriate coding and modulation (burst profile) for each allocation.
- Support for contiguous subcarrier permutations allows the scheduler to exploit multi-user diversity by allocating each subscriber to their corresponding strongest sub-channel.

3. Multicast in 802.16

The Mobile and the Fixed WiMAX MAC layers have support for multicast and broadcast services (MBS). It can be argued that broadcast is really just a form of multicast [16]. MBS related functions and features supported in the standard include [2]:

- signaling mechanisms for subscriber stations to request and establish MBS services
- subscriber stations may get access to MBS services over a single Base Station or multiple Base Stations depending on its capability and application needs
- MBS services have a certain QoS associated with them, and may be encrypted using a globally defined traffic encryption key.

- MBS traffic is placed in a separate zone within the MAC frame with its own MAP information
- methods for delivering MBS traffic to idle mode subscriber stations
- support for macro-diversity to enhance the delivery performance of MBS traffic

Multicast was a real point of emphasis for IEEE 802.16 because the committee recognized that with the development of high-end gaming and intensive video demand, there would be a growing desire for support for those types of applications in the wireless industry. As noted previously, multicast is a method of communication that allows a desirable subset of the network, or the whole network for that matter, to receive data in a highly efficient manner that will not overtax the network.

4. WiMAX Solutions to Challenges Represented in 802.11

As noted in Chapter III, IEEE 802.11 and WiFi have problems supporting both multicast and unicast streams simultaneously in its network. As we described above, this is a result of the open-loop transmission. Many of the current solutions involve changing the MAC layer and really the architecture as well. One of the solutions discussed, a leader-based approach, could offset the problem of feedback. IEEE 802.16 and WiMAX already have this approach built into its architecture with the base station, which sets up the bandwidth utilization according to several factors, including: hearability, QoS, ranging.

Here are the challenges discussed earlier with a brief description of WiMAX's capabilities to offset those deficiencies noted in Chapter III [15]:

- Since there is no feedback mechanism, it is not possible to adapt the contention window according to the network state, so multicast flows achieve a higher priority than concurrent unicast flows. Essentially, a multicast flow takes over the network and collapses it.

WiMAX uses a scheduler which ensures that every subscriber station (SS) has adequate resources to the shared medium depending on their QoS guarantee. This enables the all of customers to get a partition of the network in time slots or frequency slots depending on how the network is set up. Essentially, the MAC layer is fully responsible for allocating bandwidth resources to all users, both in the uplink and the downlink. QoS will help determine what these guarantees are but the flows will not be dependent upon the transport layer to determine which applications have priority. The individual SS, with its QoS marker, will be the determining factor. The mechanisms are already in place in WiMAX to address this deficiency within WiFi. The solution is in its architectural design and MAC layer that enables every SS to adequately be given its share of the medium. WiFi does not have this capability in its design nor its MAC layer.

The second problem of WiFi is as follows [15]:

- It is not possible to adapt the physical transmission rate to the channel characteristics, so the packets are broadcast over the wireless medium at one of the rates included in the basic rates set.

This is not a problem with WiMAX as it supports a wide variety of modulation and coding schemes and allows for those schemes to adapt on a burst-by-burst basis per link depending on channel conditions. Using a channel quality feedback indicator, the SS can provide the BS with feedback on the downlink channel quality. For the uplink, the BS can estimate the channel quality based on the received signal quality. The BS scheduler can then take into account the channel quality of each users uplink and downlink, and assign a modulation and coding scheme that will maximize the throughput for the available signal-to-noise ration. This adaptive modulation and coding significantly increases the overall system capacity, as it allows real-time trade-off between throughput and robustness on each link [1].

The various PHY layer data rates at various channel bandwidths, modulation and coding schemes supported by WiMAX are listed in Table 6. The rates shown are for the full channel bandwidth that is shared among the users. In the case of TDD, this bandwidth is also shared between the uplink and the downlink.

Channel Bandwidth		3.5 MHz	1.25 MHz	5 MHz	10 MHz	8.75 MHz ^a
PHY-Mode		256-OFDM	128-OFDMA	512-OFDMA	1024-OFDMA	1024-OFDMA
Oversampling Ratio		8/7	28/25	28/25	28/25	28/25
Modulation and Coding	Guard Time	PHY Layer Data Rates				
BPSK-1/2	1/4	1.15	N/A	N/A	N/A	N/A
	1/8	1.27	N/A	N/A	N/A	N/A
	1/16	1.36	N/A	N/A	N/A	N/A
	1/32	1.40	N/A	N/A	N/A	N/A
QPSK-1/2	1/4	2.30	0.79	3.15	6.30	
	1/8	2.53	0.88	3.53	7.07	
	1/16	2.73	0.92	3.69	7.37	
	1/32	2.80	0.96	3.84	7.68	
QPSK-3/4	1/4	3.46	1.18	4.72	9.45	
	1/8	3.80	1.32	5.30	10.60	
	1/16	4.09	1.38	5.53	11.06	
	1/32	4.20	1.44	5.76	11.52	
16-QAM-1/2	1/4	4.61	1.57	6.30	12.60	
	1/8	5.07	1.77	7.07	14.13	
	1/16	5.45	1.84	7.37	14.75	
	1/32	5.61	1.92	7.68	15.36	
16-QAM-3/4	1/4	6.91	2.36	9.45	18.89	
	1/8	7.60	2.65	10.60	21.20	
	1/16	8.18	2.76	11.06	22.12	
	1/32	8.41	2.88	11.52	23.04	

Table 6. PHY Layer Data Rates at Various Channel Bandwidths (From: [2]).

- Lastly, there is no way to retransmit lost packets at the MAC layer, and definitely not at the IP or transport (UDP) layers, so the multicast transmission is more lossy than unicast flows, which degrades this application's performance [15].

Since one of the biggest beneficiaries of multicast transmissions is usually time-sensitive data, such as video and voice, there may not be a real need to ensure that the complete transmission is received from the sender. However, there is a quality issue that needs to be attained to ensure that particular applications obtain enough packet/bandwidth resources to provide a clear output. Even though some lossiness is assumed when transmitting time-sensitive data, there still needs to be a mechanism in place to retransmit if necessary. The current approach for downstreaming video and

perhaps even voice is to buffer a part of the output to compensate for any lost packets or damaged packets during the transmission. With that in mind, there are two mechanisms in place for WiMAX which will overcome this deficiency present in WiFi. They are: a retransmission capability and QoS guarantees.

Retransmission Capability – One of the retransmission capabilities touted by WiMAX is called ARQ – automatic repeat request. The ARQ mechanism is an optional part of the MAC layer and can be enabled on a per-connection basis [5]. The per-connection ARQ and associated parameters are specified and negotiated during connection creation or change. The ARQ feedback information can be sent as a standalone MAC management message on the appropriate basic management connection or piggybacked on an existing one. Transmitter and receiver state machine operations include comparing fragment sequence numbers and taking actions based on which is larger or smaller. An ARQ fragment may be in one of the following four states – not-sent, outstanding, discarded, and waiting for retransmission. Depending on the time in the cycle determines to which state it falls into. For each ARQ fragment accepted fully and without errors, an acknowledgement message is sent to the transmitter. It is important to understand that although this capability is extremely useful, it can be extremely taxing on a network if not utilized correctly. A better mechanism may be the QoS standards which may incorporate this ARQ request into some of its higher standards.

QoS Guarantees – As noted already in this section, the QoS guarantees will allow for this sort of assuredness. Multicast services will have a higher priority than other delivery services because of the nature of its transmission. This will have less chance of being dropped than other packets due to its priority. These guarantees also ensure that if a packet is of a higher priority, retransmission is afforded to them whereas the lower priority packets, or best effort services, may not have that capability in its design.

B. POTENTIAL APPLICATIONS & SERVICES PROVIDED BY WIMAX

Demand for broadband services is growing at an increasing rate, and broadband is rapidly becoming a necessity for the enterprise and residence markets. Wireless delivery of broadband is introducing a new degree of flexibility and universal connectivity,

ushering in the new era of “personal lifestyle” technology applications [21]. WiMAX is still early in its development and deployment, although it has been partly available in the commercial industry for almost two years. Sprint Nextel, along with many other major telecommunication firms, have been investing billions of dollars into it for utilization in their own networks [2]. Many cities, both foreign and abroad, are looking at it as an alternative to metropolitan-sized wireless data communication. South Korea has developed a similar technology, known as WiBro, which is already functioning rather well and has already been assured to be compatible with WiMAX. These two technologies will be intertwined and will be pivotal in the establishment of a Global Area Network, or GAN, in the not so distant future. There has been much investment and development on this particular technology, and there is a growing list of applications (Table 7) and services (Table 8) this technology can provide and fulfill.

Class Description	Real Time?	Application Type	Bandwidth
Interactive Gaming	Yes	Interactive Gaming	50 - 85 kbps
VoIP, Video Conference	Yes	VoIP	4 - 64 kbps
		Video Phone	32 - 384 kbps
Streaming Media	Yes	Music/Speech	5 - 128 kbps
		Video Clips	20 - 384 kbps
		Movies Streaming	> 2 Mbps
Information Technology	No	Instant Messaging	< 250 byte messages
		Web Browsing	> 500 kbps
		Email (with attachments)	> 500 kbps
Media Content Download (Store and Forward)	No	Bulk Data, Movie Download	> 1 Mbps
		Peer-to-Peer	> 500 kbps

Table 7. WiMAX Potential Applications (From: [22]).

	Flexible Architecture	High Security	WiMAX QoS	Quick Deployment	Multi-Level Service	Interoperability	Portability	Mobility	Cost-Effective	Wider Coverage	NLOS	High Capacity
Cellular Backhaul				X					X			X
WSP Backhaul				X					X			X
Banking Networks	X	X	X						X		X	
Education Networks	X		X						X	X		
Public Safety	X	X	X	X			X	X			X	
Offshore Communications	X		X				X	X		X	X	
Campus Connectivity	X	X	X									X
Temporary Construction			X	X			X				X	
Theme Parks	X		X				X	X			X	
WSP Access Network		X	X		X	X			X		X	X
Rural Connectivity			X			X			X	X		
Military Battlefield	X	X		X			X	X				

Table 8. WiMAX Potential Services (From: [22]).

1. Internet Access

Wireless Service Providers (WSPs) could use WiMAX networks to provide connectivity to residential, business, and military customers, as noted in Figure 21. The WSP could be a CLEC (Competitive Local Exchange Carriers) that is starting with little or no installed infrastructure. Since WiMAX is easy to deploy, the CLEC can quickly install its network and be prepared to compete against other networks or introduce a network to a new area. The WiMAX built-in QoS mechanism is highly suited for the mix of traffic carried by the CLEC. The QoS MAC also offers multi-level service to address the variety of customer service needs. A common network platform, offering voice, data and video, is highly attractive to end customers, because it presents a one-stop shop and a single monthly bill. This would be very similar to the cable industry's "Triple Play."

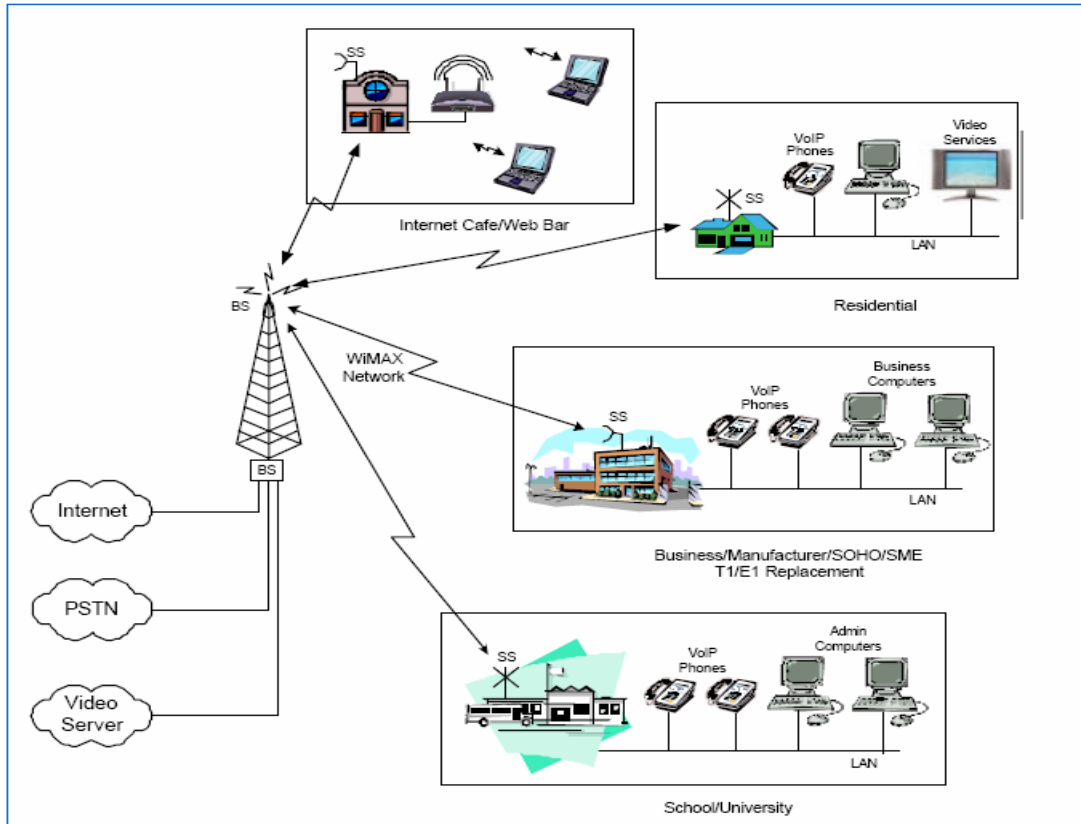


Figure 21. Wireless Service Provider Utilizing WiMAX (From: [22]).

Cellular operators may also be interested in applying WiMAX in their networks. They could use WiMAX to augment their network because they already have towers, billing infrastructure and a customer base in place, but the deployment of a WiMAX solution will expand their market presence in their service area. Wired solutions are costly because of the required upfront infrastructure necessary. In particular, wired solutions are not suited for markets in developing countries, where there is very little infrastructure, or in the less-populated areas of developed countries, such as rural areas, small towns or the suburban edges of major centers.

2. Local Loop Alternative

Last-mile access is a term which describes the last leg of getting the signal from the provider to the subscriber. There is no doubt that WiMAX is just another alternative

to achieve this, as noted in the previous section. But, WiMAX offers another capability which many other alternatives do not. The ability to open up a market where there is no existing infrastructure in place. Service providers can use WiMAX networks to deliver service to underserved markets in rural areas and the suburban outskirts of cities, as shown in Figure 22. The delivery of rural connectivity is critical in many developing countries and underserved areas of developed countries, where little or no infrastructure is available. Rural connectivity delivers much-needed voice telephony and Internet service. Since the WiMAX solution provides extended coverage, it is a much more cost-effective solution than wired technology in areas with lower population densities.

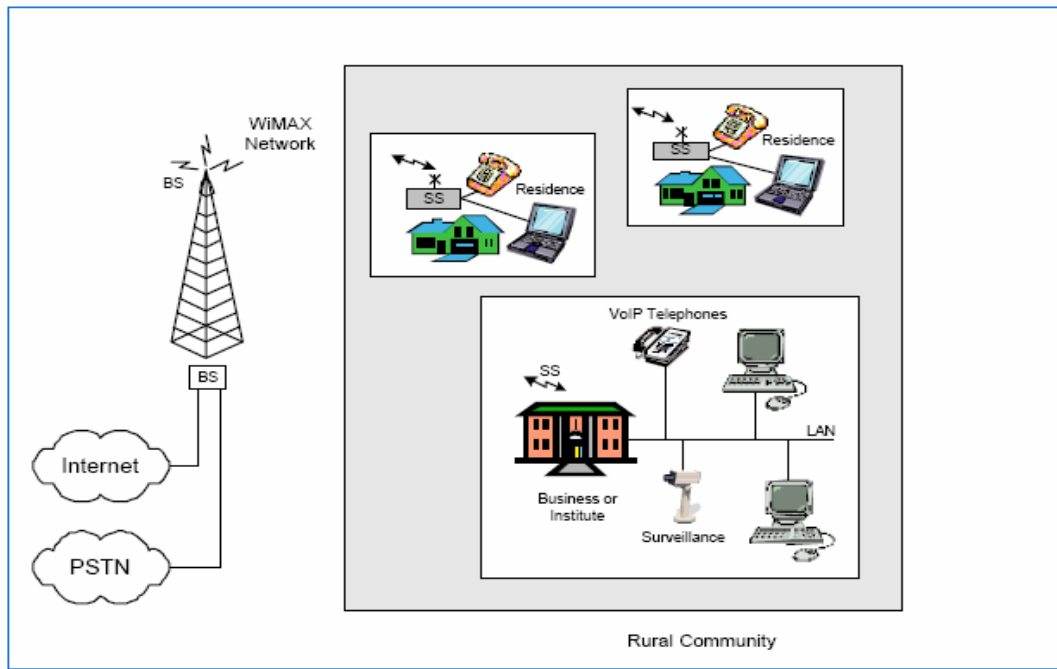


Figure 22. WiMAX Delivery to Rural Areas (From: [22]).

3. Backhauling

Access networks may be based on WiFi, WiMAX or any proprietary wireless access technology. But this allows for another service which WiMAX can provide: backhauling. This is the middle leg of getting the signal to the subscriber. Due to

WiMAX's range, which is estimated at 70km with sophisticated antennas, it is able to cover large distances rather quickly with substantial bandwidths and again limited infrastructure [1]. Figure 23 visually describes the idea of backhauling.

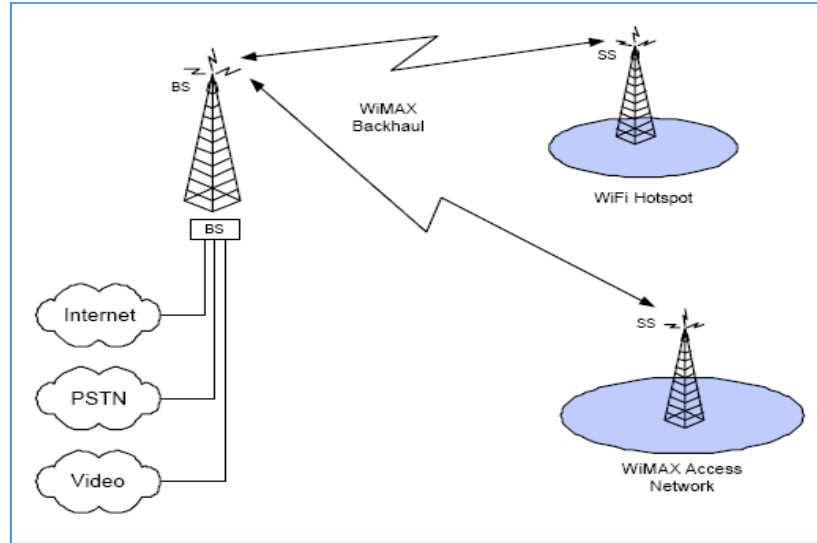


Figure 23. WiMAX Backhauling Capability (From: [22]).

In addition to WSPS, WiMAX can also provide backhaul for cellular users. The market for cellular services is becoming more and more competitive. To stay in the business, cellular operators are constantly looking for ways to reduce operating costs. Backhaul costs for cellular operators represent a significant portion of their recurring costs. WiMAX can provide Point-to-Point links, with data rates capable of supporting multiple E1/T1s Cellular operators can therefore use WiMAX equipment to backhaul Base Station traffic to their Network Operation and Switching Centers, as shown in Figure 25.

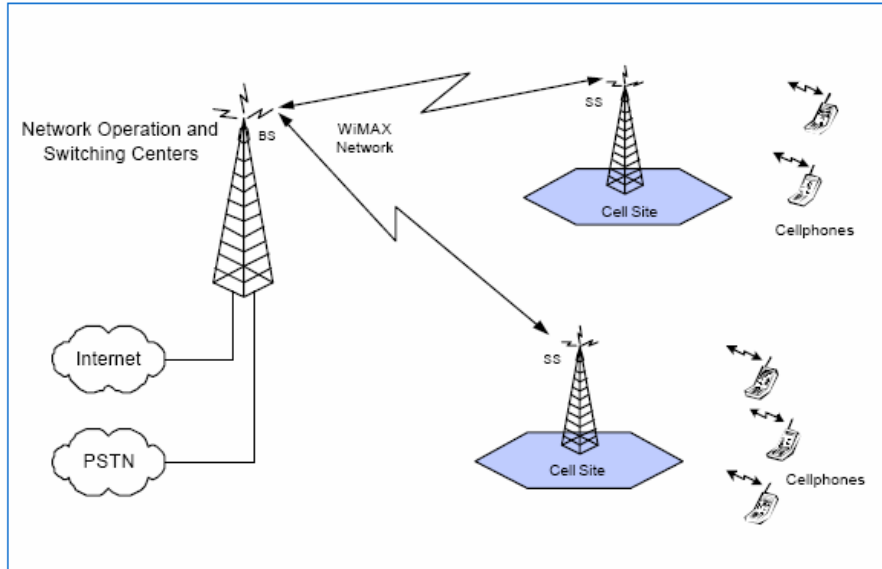


Figure 24. WiMAX Backhauling Capability for Cellular (From: [22]).

4. Mobility

One of the strongest features of WiMAX is its mobility piece. Known as mobile WiMAX and based on IEEE 802.16e-2005, this feature will allow for unprecedented applications as well as desirable services. Bandwidths at levels as high as 10 Mbps will be available to roaming devices, allowing them to support applications such as gaming, interactive video, broadband content download in real time, and high-quality music delivery, along with a host of other interactive applications. This mobility will enable a subscriber to stay connected while traveling in a car, on a train, or whatever land-based platform you prefer. It is very plausible to imagine many different types of applications which will necessitate this sort of connectivity. Imagine your car connected to a central base station, much like the modern automobile GPS systems, and with it your car transmits and receives valuable information regarding you or your car. This could be driving information, automated driving, whatever. The possibilities are entirely endless with this sort of mobile and roaming connectivity. This is a great step towards the global area network (GAN) which has been desired for so long.

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V. CONCLUSION AND RECOMMENDATIONS

A. OVERVIEW

This thesis analyzed the multicast delivery of IEEE 802.16 and its corresponding Worldwide interoperability for Microwave Access (WiMAX) technology. This delivery method is ideal for certain multimedia applications and is extremely beneficial for wireless networks. Multimedia applications should continue to be in high demand in the telecommunications industry now and in the future. IEEE 802.11 wireless LANs are one of the fastest growing network technologies in the wireless communications field. With that, there will be an increasing need for wireless media to handle such high data-rate time-sensitive traffic. However, IEEE 802.11 and its corresponding Wireless Fidelity (WiFi) technology have difficulty handling both multicast and unicast traffic in a network. Today, most of our personal digital assistants (PDAs) and laptops include by default, a WiFi interface. There is also a growing desire for multimedia applications to be delivered to these devices. This thesis presents WiMAX as a potential alternative to this problem. It was designed to handle such applications due to its Quality of Service (QoS) features and robust MAC layer.

There are severe issues that result when multicasting in WiFi products. The problem is the MAC layer sends multicast packets in open-loop as broadcast packets [4]. This means there will be no acknowledgements of receipt. This open-loop transmission mechanism causes three problems:

- Since there is no feedback mechanism, it is not possible to adapt the contention window according to the network state, so multicast flows achieve a higher priority than concurrent unicast flows. Essentially, it takes over the network and collapses it.
- It is not possible to adapt the physical transmission rate to the channel characteristics, so the packets are broadcast over the wireless medium at one of the rates included in the basic rates set.

- Lastly, there is no way to retransmit lost packets at the MAC layer, and definitely not at the IP or transport (UDP) layers, so the transmission is more lossy than unicast flows, which degrades this application's performance [15].

There has been ongoing research in the IEEE 802.11 standard to account for these issues. Many of them involve substantial redesign in the MAC layer. These proposed solutions are not going to completely solve the problem of simultaneous unicast and multicast traffic operating together in a shared network. The reason is that WiFi centers on a contention window for access. This is not a reliable method for access across the network. A better method exists in WiMAX which uses more of a time-slotted access window. WiMAX is an emerging technology and due to its design, is resilient enough to handle many different types of applications and services. Its QoS features and well-designed MAC layer will only enhance the powerful broadband wireless features it promotes. Undoubtedly, WiMAX is truly a giant step towards the goal of a Global Area Network (GAN).

B. MULTICAST IN 802.16

Multicast delivery services are an efficient way of transmitting data to a group or subset of users. It eliminates the redundant transmissions that would usually occur in unicast type transmissions. Applications and services are demanding this type of delivery mechanism as more and more of them use intensive data streams with high data rates. Existing wireless technology cannot handle this type of delivery adequately in a multidimensional network. However, IEEE 802.16 and WiMAX have the ability due to its QoS guarantees and MAC layer features which allow for simultaneous multi-delivery services. These features also allow for dynamic transmission rates perfectly suited for each flow as well as the whole network. There are also features in place which allow for simultaneous unicast, multicast, and broadcast services to operate in an efficient manner and most importantly, operate in harmony according to their individual QoS guarantee. These features and WiMAX's overall design make it a perfect transmission media for such applications.

WiMAX uses a scheduler which ensures that every subscriber station (SS) has adequate resources to the shared medium depending on their QoS guarantee. This enables the customers, all of them to get a partition of the network in time slots or frequency slots depending on how the network is set up. Essentially, the MAC layer is fully responsible for allocating bandwidth resources to all users, both in the uplink and the downlink. QoS will help determine what these guarantees are but it will not be dependent upon the transport layer to determine which a priority is and which is not. The individual SS, with its QoS marker, will be the determining factor. There are mechanisms already in place within WiMAX that addresses this WiFi deficiency. The solution is in its architectural design and MAC layer which enables every SS to adequately garner its share of the medium. WiFi does not have this capability in its design nor its MAC layer.

WiMAX supports a wide variety of modulation and coding schemes that allows for adaptation on a burst-by-burst basis per link depending on channel conditions. Using a channel quality feedback indicator, the SS can provide the BS with feedback on the downlink channel quality. For the uplink, the BS can estimate the channel quality based on the received signal quality. The BS scheduler can then take into account the channel quality of each users uplink and downlink, and assign a modulation and coding scheme that will maximize the throughput for the available signal-to-noise ratio. This adaptive modulation and coding significantly increases the overall system capacity, as it allows real-time trade-off between throughput and robustness on each link [1].

There are two mechanisms in place for WiMAX which will overcome the lossiness deficiency present in WiFi. They are: a retransmission capability and again, QoS guarantees.

Retransmission Capability – One of the retransmission capabilities touted by WiMAX is called ARQ – automatic repeat request. The ARQ mechanism is an optional part of the MAC layer and can be enabled on a per-connection basis [5]. The per-connection ARQ and associated parameters are specified and negotiated during connection creation or change. The ARQ feedback information can be sent as a standalone MAC management message on the appropriate basic management connection or piggybacked on an existing one. Transmitter and receiver state machine operations

include comparing fragment sequence numbers and taking actions based on which is larger or smaller. An ARQ fragment may be in one of the following four states – not-sent, outstanding, discarded, and waiting for retransmission. Depending on the time in the cycle determines to which state it falls into. For each ARQ fragment accepted fully and without errors, an acknowledgement message is sent to the transmitter. It is important to understand that although this capability is extremely useful, it can be extremely taxing on a network if not utilized correctly and most importantly for the correct traffic. A better mechanism may be the QoS standards which may incorporate this ARQ request into some of its higher standards.

QoS Guarantees – As noted already in this section, the QoS guarantees will allow for this sort of assuredness. Multicast services will have a higher priority than other delivery services due to the nature of its transmission. Because of this it will have a less likely chance of being dropped than other packets due to its priority. These guarantees also ensure that if a packet is of a higher priority, retransmission is afforded to them whereas the lower priority packets, or best effort services, may not have that capability in its design.

C. POTENTIAL APPLICATIONS AND SERVICES FOR WIMAX

IEEE 802.16 and its WiMAX technology have enough flexibility and durability in its design to host a wide variety of applications and services. They consist of both point to point (PTP) and point to multipoint (PTMP) types of applications. This is the probably the greatest strength in that it can be applied to one of many different types of network configurations, including cable, cellular, wireless, and a host of others as mentioned in Chapter IV. Additionally, its low cost infrastructure will prove to be an added feature in environments where there is no existing infrastructure such as rural areas and in developing countries. Additionally, WiMAX can operate as a WMAN (wireless metropolitan area network), it can be a part of the Last-Mile solution, it can carry long haul communications over large distances, and it is this variety which will enable WiMAX to thrive in the open market. Cellular and data network companies both have

invested billions into utilizing this capability on their own networks. WiMAX can be thought of as a multidimensional tool in the “toolbox of telecommunications.”

The first major application of WiMAX is Internet Access. Wireless Service Providers (WSPs) could use WiMAX networks to provide connectivity to residential, business, and military customers. The WSP could be a CLEC (Competitive Local Exchange Carriers) that is starting with little or no installed infrastructure. Since WiMAX is easy to deploy, the CLEC can quickly install its network and be prepared to compete against other networks or introduce a network to a new area. The WiMAX built-in QoS mechanism is highly suited for the mix of traffic carried by the CLEC. The QoS MAC also offers multi-level service to address the variety of customer service needs. A common network platform, offering voice, data and video, is highly attractive to end customers, because it presents a one-stop shop and a single monthly bill. This would be very similar to the cable industry’s “Triple Play.”

The second major potential service which WiMAX can provide is a local loop alternative. Last-mile access is a term which describes the last leg of getting the signal from the provider to the subscriber. There is no doubt that WiMAX is just another alternative to achieve this. But, WiMAX offers another capability which many other alternatives do not. The ability to open up a market where there is no existing infrastructure in place. Service providers can use WiMAX networks to deliver service to underserved markets in rural areas and the suburban outskirts of cities. The delivery of rural connectivity is critical in many developing countries and underserved areas of developed countries, where little or no infrastructure is available. Rural connectivity delivers much-needed voice telephony and Internet service. Since the WiMAX solution provides extended coverage, it is a much more cost-effective solution than wired technology in areas with lower population densities.

The third major alternative focuses on data backhauling. Access networks may be based on WiFi, WiMAX or any proprietary wireless access technology, but they need to be backhauled to the main provider. Backhauling can be thought of as the middle leg of getting the signal to the subscriber. Due to WiMAX’s range, which is estimated at 70km with sophisticated antennas, it is able to cover large distances rather quickly with

substantial bandwidths and again limited infrastructure [1]. In addition to WSPS, WiMAX can also provide backhaul for cellular users. The market for cellular services is becoming more and more competitive. To stay in the business, cellular operators are constantly looking for ways to reduce operating costs. Backhaul costs for cellular operators represent a significant portion of their recurring costs.

The last major service which could be provided by WiMAX centers on its mobility feature. One of the strongest features of WiMAX is its mobility piece. Known as mobile WiMAX and based on IEEE 802.16e-2005, this feature will allow for unprecedented applications as well as desirable services. Bandwidths at levels as high as 10 Mbps will be available to roaming devices, allowing them to support applications such as gaming, interactive video, broadband content download in real time, and high-quality music delivery, along with a host of other interactive applications. This mobility will enable a subscriber to stay connected while traveling in a car, on a train, or whatever land-based platform you prefer. It is very plausible to imagine many different types of applications which will necessitate this sort of connectivity.

D. FUTURE WORKS

This Thesis focused on analyzing IEEE 802.16 and its WiMAX technology in relation to multicasting and it also focused on possible applications and services for WiMAX technology. Commercial off the shelf equipment is beginning to become available to the public and many corporations are in the final stages of integrating this technology into their networks. When this begins to present itself more visibly, there will definitely need to be testing performed to note its advantages and limitations. This is vital to the improvement of not only the technology, but other alternative forms of broadband wireless. It will important to see if WiMAX truly can handle multicast applications, implement QoS features, and a host of other features it looks capable of doing according to its specifications. But truly, experimentation will ultimately decide its worth and its future in the market.

Some questions that need to be addressed are:

1. Using Dujovne and Turetti's [3] benchmarks, how does WiMAX compare with their research on WiFi?
2. Are there applications emerging which would be ideal for multicast in WiMAX? Which ones are better than others? Which do not give one a competitive advantage over some other wireless technologies?
3. How does some of the proprietary wireless technologies deal with multicast delivery? Are they compatible with WiMAX? Are they better than WiMAX?
4. What are some military applications for WiMAX?
5. What about scalability and WiMAX? What about its security?

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